Cross-linguistic transfer in bilinguals reading in two alphabetic orthographies: The grain size accommodation hypothesis.

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Abstract

Reading acquisition is one of the most complex and demanding learning processes faced by children in their first years of schooling. If reading acquisition is challenging in one language, how is it when reading is acquired simultaneously in two languages? What is the impact of bilingualism on the development of literacy? We review behavioral and neuroimaging evidence from alphabetic writing systems suggesting that early bilingualism modulates reading development. Particularly, we show that cross-linguistic variations and cross-linguistic transfer affect bilingual reading strategies as well as their cognitive underpinnings. We stress the fact that the impact of bilingualism on literacy acquisition depends on the specific combination of the languages learned and does not manifest itself similarly across bilingual populations. We argue that these differences can be explained by variations due to orthographic depth on the grain size used to perform reading and reading-related tasks. Overall, novel hypotheses are proposed to shed light on behavioral and neural processes variability observed in reading skills and in the manifestations of developmental dyslexia in bilinguals.

Keywords: Bilingualism, Reading development, Orthographic depth, Grain size

1. Introduction

Reading acquisition involves the recruitment and coordination of multiple cognitive and neural resources to build-up fluent letter-to-sound mappings. However, the development of these complex mechanisms is not equal across languages. In alphabetic orthographies, the degree of difficulty affecting reading acquisition is modulated by factors linked to the complexity of letter-sound associations and to the size of the grain used in reading and reading related tasks. While research has endeavoured to improve our knowledge of reading acquisition across languages in monolingual settings, the number of behvioural (and neuroimaging) studies that look at reading development in bilinguals is rather scarce, making this population a clear outlier in this field of research. However, the rapid increase in the number of children acquiring reading in two languages simultaneously begs for more research on this question. The main goal of this paper is to complement classic monolingual-centered research and take a step forward in proposing a novel framework on reading acquistion in bilinguals that will help to address unresolved questions on this topic: namely, does bilingualism affect reading acquisition? And, if so, how does this influence manifest itself?

In that aim, firstly, we present work that highlights the cognitive and neural bases of reading skills and reading sub-skills (auditory phonology and visual attention) in the context of monolingual and bilingual reading acquisition in alphabetic orthographies. Secondly, we review behavioral and neuroimaging evidence in monolinguals and bilinguals showing how orthographic-specific modulations shape the use of reading strategies and the size of the grain used in reading and reading-related tasks. Thirdly, we propose the grain size accommodation hypothesis that should contribute to predict the manifestations of cross-linguistic transfer on the development of reading in early bilinguals.

2. Neural and cognitive networks of reading skills and sub-skills

2.1. Reading skills

In all alphabetic writing systems, the reading procedure (or strategy) referred to as '*phonological decoding'* whereby children decipher the phonology of unfamiliar orthographic strings provides the bases for reading acquisition. Solid phonological decoding skills will foster, through a self-teaching mechanism, the development of an orthographic lexicon to enable fast and fluent reading (Share, 1999, 2004; Ziegler, Perry, and Zorzi, 2014). Consequently, efficient orthographic and phonological cognitive processes are necessary to crack the orthographic code and learn to read fluently. Two orthographic routes may be used to access phonological representations. On the one hand, fine grain orthographic coding of graphemes and their respective order in a word is responsible for retrieving phonemes and accessing whole-word phonology. On the other hand, coarse grain orthographic computations will process the necessary information to *guess* the orthographic and phonological identity of a word as a whole (Grainger & Ziegler, 2011).

Therefore, the brain signature of learning to read should illustrate how beginner readers progressively tune the neural populations in charge of *the mapping* between orthography and phonology, i.e., graphemes and phonemes in the case of alphabetic languages. In fact, good functional and structural connections between brain areas subtending grapheme-to-phoneme mapping is essential to develop reading in alphabetic languages (De Schotten, Cohen, Amemiya, Braga, and Dehaene, 2012).

As a consequence of an active use and exposure to grapheme-to-phoneme mappings, activity around a small area located in the left ventral occipital-temporal (vOT) cortex (the so-called visual word form area, VWFA, Cohen, Lehéricy, Chochon, Lemer, Rivaud, and Dehaene, 2002) has been shown to emerge (Brem et al., 2010). It has been proposed that the lateralization of this area to the left hemisphere reflects the influence of print phonology on the orthographic computations performed by neurons located in this visual region (e.g., Yoncheva, Zevin, Maurer, and McCandliss, 2010). This is in line with the existence of left-sided dorsal temporo-parietal network within the reading network, that includes the inferior parietal lobule and the posterior superior temporal region: the former would be specifically involved in attentional shifting linked to serial decoding mechanisms (Carreiras, Quiñones, Hernández-Cabrera, and Duñabeitia, 2014; Richlan, 2014; Taylor, Rastle and Davis, 2013), whereas the latter may have a preferential role to play in grapheme-to-phoneme mapping (van Atteveldt & Ansari, 2014). As the amount of reading experience increases, the left vOT cortex takes the control of the automatic retrieval of orthographic representations through the parallel computation of the letters of orthographic inputs. Therefore, the left vOT cortex seems to be necessary for the development of the automatic recognition of lexical orthographic forms, i.e., the lexical reading procedure, in particular because it also connects to regions that perform lexico-semantic analysis (Yeatman, Rauschecker, and Wandell, 2013) such as the left medial temporal lobe (Vigneau et al., 2006). Overall, the aforementioned reading network plays a central role in the acquisition of visual word identification (Carreiras, Armstrong, Perea, and Frost, 2014; Jobard, Crivello, and Tzourio-Mazoyer 2003; Sandak, Mencl, Frost, and Pugh, 2004; Schlaggar & McCandliss, 2007). Moreover, a hypo-activation of parts of this network is the signature of reading disorders across languages (Richlan, 2014; Richlan, Kronbichler, and Wimmer, 2009).

2.2. Reading sub-skills: auditory phonology and visual attention span

It is not clear whether the quality of neural activity and connectivity within this reading network is the proximal cause or a mere consequence of reading outcomes. In fact, it is important to note that the reading activity itself feeds from cognitive computations performed by several other brain areas that don't overlap with the neural circuitry described above. The cognitive skills (hereafter referred to as *reading sub-skills*) which arise from the activation of these areas represent the pre-requisites of normal reading acquisition: they correspond to a pool of skills that are not directly engaging orthography-phonology mapping mechanisms and reading strategies *per se*, but without which the acquisition of such strategies would be delayed or impaired. A large amount of developmental research, including important work on developmental dyslexia, has highlighted several fundamental reading sub-skills that might independently contribute to reading acquisition, in line with a multifactorial approach to understand typical and atypical reading development (Bosse, Tainturier, and Valdois, 2007; White et al., 2010; Wolf & Bowers, 1999). Developmental dyslexia is diagnosed when an unexpected persistent low reading proficiency is achieved despite the absence of other factors that could explain the reading difficulties (i.e., sensory or psychiatric disorders, abnormal schooling, low IQ). Research trying to identify the proximal cause(s) of this reading disorder has shed light on the cognitive pre-requisites of reading acquisition. In light of such research, we will focus on two cognitive reading sub-skills, namely 'auditory' phonology and visual attention.

Auditory phonology refers to processes that require the analysis of the sound structure of linguistic stimuli. These skills, acquired in infancy from the analysis of speech streams before any exposure to print takes place, are thought to contribute significantly to reading development and grapheme-to-phoneme conversion in particular (Snowling, 2000; Snowling, 2008). Therefore, an auditory phonological deficit would explain why dyslexic individuals fail to learn to read fluently (Ramus et al., 2003). So far, several phonological components have been identified and shown to contribute to reading development (i.e., phonological awareness, phonological short term memory, phonological access/fluency), although it is still a matter of debate whether they tap into independent constructs (Protopapas, 2014) or if they equally contribute to reading (Melby-Lervag et al., 2012). Ramus and Szenkovits (2008) explored more deeply the nature of the phonological deficit and proposed that the access to phonological representations (and not the quality of these representations) is the core phonological problem in dyslexia (see also Ramus, 2014). A recent neuroimaging study supports this hypothesis. Boets et al. (2013) report that the left-sided brain network subtending phonological reading sub-skills, i.e., the superior temporal gyrus and the inferior frontal gyrus, is less strongly connected in dyslexic than in skilled readers. Interestingly, these phonological regions are functionally and structurally linked to the reading networks (e. g., Cao, Bitan, and Booth, 2008; Steinbrink, Vogt, Kastrup, Müller, Juengling, Kassubek, and Riecker, 2008; Van der Mark et al., 2011; Vandermosten, Boets, Poelmans, Sunaert, Wouters, and Ghesquière, 2012), which explains why their role in reading must be significant. Studies conducted across alphabetic languages report that these phonological abilities tend to have the strongest contribution to reading development at the first stages of reading acquisition, when most of the orthographic inputs are unfamiliar and need to be decoded phonologically (Bosse & Valdois, 2009; Vaessen, Bertrand, Tóth, Csépe, Faísca, Reis, and Blomert, 2010; Ziegler et al., 2010).

Unlike auditory phonology, the role of visual attention in reading has received less interest in developmental research and has been subject to debate (Goswami, 2015; Skottun & Skoyles, 2006). However, there is increasing evidence that visual attentional skills do contribute to literacy acquisition and that they may even play a causal role in reading outcomes (Franceschini, Gori, Ruffino, Viola, Molteni, and Facoetti, 2010; Onochie-Quintilla, Defior, and Simpson, 2017; Valdois, Peyrin, Lassus-Sangosse, Lallier, Démonet, and Kandel, 2014). So far, research has highlighted two (possibly independent) main visual attentional components important for learning to read: covert spatial visual attentional shifting abilities and visual attention span skills (Lallier & Valdois, 2012). First, covert spatial attentional shifting corresponds to spatial changes in the spotlight of attention occurring without eye movement. The idea is that visual attention is able to shift between different spatial locations within a string of letters while the eyes remain fixated. These covert visual attention skills would be mainly necessary for pseudoword reading and the use of phonological decoding strategies (Facoetti et al., 2006; Hari & Renvall, 2001; Onochie-Quintilla et al., 2017; Perry, Ziegler, and Zorzi, 2010), since they would subtend the sequential orthographic parsing strategies that facilitate grapheme-to-phoneme conversions. In line with this idea, covert visual attentional shifting skills have been shown to correlate with auditory phonological abilities (Lallier, Donnadieu, Berger, and Valdois, 2010; Lallier & Valdois, 2012). In relation to this, Richlan et al. (2009; 2011) found a consistent atypical functioning of left dorsal inferior parietal sites in impaired readers (supramarginal gyrus in particular) which may be directly involved in sequential visual attention processes at play during phonological decoding (Richlan, 2014). This data is also in line with the classical involvement of the parietal junction in attentional shifting and orientation (Astafiev, Shulman, and Corbetta, 2006; Corbetta & Shulman, 2002; Mars, Sallet, Schüffelgen, Jbabdi, Toni, and Rushworth, 2012). The second visual attention component, the visual attention span, contributes to reading independently from the aforementioned phonological skills (Bosse et al., 2007; Bosse & Valdois, 2009) and the verbal nature of the stimuli to be processed (Lobier, Peyrin, Le Bas, and Valdois 2012). Visual attention span skills are defined as the number of visual elements that can be processed simultaneously in a multi-element array, and are classically measured with the global and partial report tasks (Bosse et al., 2007). In these tasks, an array of five visual elements is presented for no more than 200 ms (time for one fixation) and participants have either to report all the elements identified with no order constraint (global report, see Figure 1.a.) or a single cued element (partial report, see Figure 1.b.).

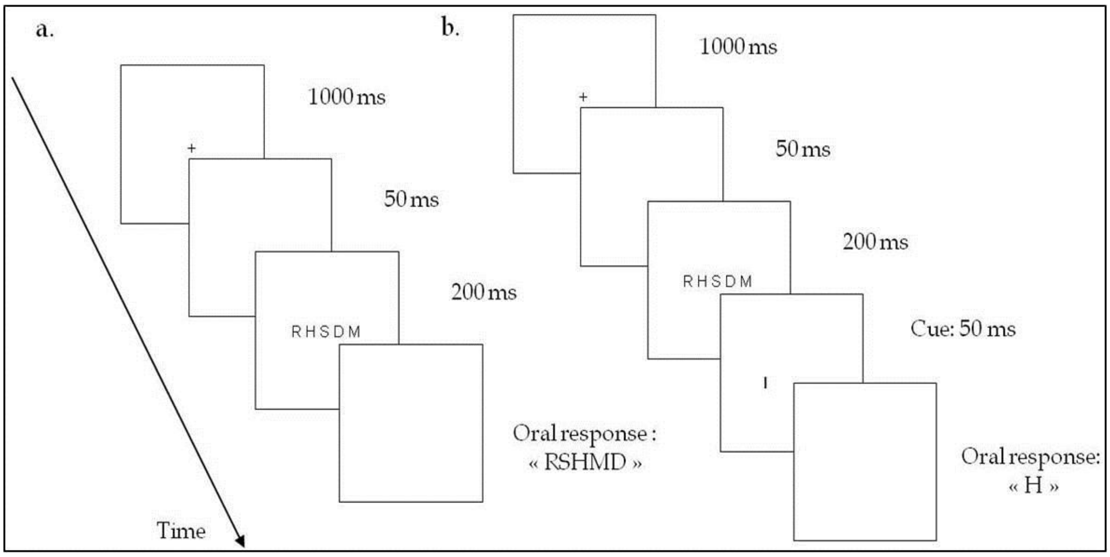

Figure 1. Schematic illustration of the whole and partial report tasks. The whole report task requires naming as many of the 5 consonants as possible without order constraint (a.). The partial report task requires a single cued letter to be named (b.).

These skills are thought to support the encoding of orthographic chunks as a whole in memory (Bosse, Chaves, Largy, and Valdois, 2013). They would engage the simultaneous dimension of visual processing in contrast to the covert spatial visual attentional shifting skills presented above that would tap into sequential processing (Lallier et al., 2010; Lassus-Sangosse, N'Guyen-Morel, and Valdois, 2008). The superior parietal lobules have been shown to be recruited during tasks tapping visual attention span abilities, in line with the attentional interpretation of these skills (Peyrin, Démonet, N'guyen-Morel, Le Bas, and Valdois, 2011; Peyrin, Lallier, and Valdois, 2008). Interestingly, the superior parietal lobule has not been directly ascribed to the reading network *per se* (unlike the inferior parietal lobule), and may instead be involved in the pre-orthographic processing of letter strings (Carreiras et al., 2014; Lobier, Peyrin, Le Bas, and Valdois, 2012; Reilhac, Peyrin, Démonet, and Valdois, 2013). Accordingly, dyslexic adults and children with a visual attention span disorder exhibit a hypo-activation of the superior parietal lobule bilaterally, whereas the brain activity of dyslexic participants with a pure auditory phonological deficit exhibit a hypo-activation of the left inferior frontal gyrus (Peyrin, Lallier, Demonet, Pernet, Baciu, Le Bas, and Valdois 2012). Its role would be potentially important when the letter strings are not presented in a familiar format and would therefore be in charge of the difficult analysis of multiple visual elements (Cohen, Dehaene, Vinckier, Jobert, and Montavont, 2008) before their processing can be relayed by the left vOT cortex (see also Lobier et al., 2012 for a more detail account of the role of the superior parietal lobules in reading and its connections with the left vOT area). In line with this idea, Yeatman et al. (2014) reported the existence of a white matter tract that connects the vOT to the intra parietal sulcus.

Overall, research shows that both auditory phonology and the visual attention span are cognitive reading sub-skills that contribute to typical and atypical reading development and whose brain underpinnings are connected to the areas of the classical reading network, although they don't generally overlap with it[1]. Importantly, a pure phonological deficit (i.e., without visual attention span impairment) and a pure visual attention span reduction (i.e., absence of any phonological deficit) are thought to potentially cause dyslexia (Valdois et al., 2003). However, the prevalence of either type of deficit may differ within the dyslexic population. For example, Saskida et al. (2016) show that pure phonological deficits associated with dyslexia were actually much more frequent than pure visual attention span disorders in a French child population. However, Bosse et al. (2007) found a relatively equal proportion of the two dyslexic types in French and British groups of children. More prevalence studies are needed within and across languages to better characterize the scope of such multifactorial hypothesis of dyslexia.

In the next section, we will describe cross-linguistic research in monolinguals and bilinguals. We will focus on the effects of orthographic depth (i) on reading strategies and (ii)

[1] The left inferior frontal gyrus has been generally included in the reading network (e.g., Pugh et al., 2000), although its role in reading points towards the access of auditory phonological representations, therefore, encompassing also pure auditory phonological processing (Boets et al., 2013).

on reading sub-skills (auditory phonology and visual attention span). The issue of cross-linguistic transfer based on orthographic depth factors in bilinguals will be addressed subsequently.

3. Cross-linguistic differences on reading strategies: the role of orthographic depth and its consequence on the processing grain size.

One of the most studied modulator of reading acquisition across languages is orthographic depth. Alphabetic writing systems differ on the complexity, consistency, and predictability with which the graphemes map into their corresponding phonemes (Schmalz, Marinus, Colthear, and Castles, 2015). In Spanish, a shallow orthography, these relations are (mostly) univocal: the letter "o" always converts to the sound /o/ and the phoneme /o/ is always written with the letter "o". However, in deep orthographies like French, these mappings are far more complex and irregular (e.g., Rey & Schiller, 2005). First, the same letter can be found in various French graphemes or the same phoneme can be written with different graphemes depending on the word it appears in (i.e., the *complexity* issue): the grapheme "o" sounds like /o/, but when the letter "o" is present in 2-letter grapheme "**o**u" it is pronounced /u/, and in the 3-letter graphemes "**o**in" it is pronounced /wẽ/; the phoneme /o/ is spelt "o" in "p**o**ésie" , "ot" in "p**ot**", "au" in "p**au**vre", "eau" in "p**eau**". Second, some graphemes map into phonemes in unpredictable ways, and the grapheme-to-phoneme conversion rule will solely depend on the word orthographic context (i.e., the *regularity* issue): the grapheme, "**on**" is pronounced /õ/ in "m**on**stre", "m**on**tagne", "m**on**tre", "m**on**t", but /ə/ in "monsieur"; "s" is pronounced /s/ in "vrai**s**emblable" but /z/ in "dé**s**uet", "mai**s**on", "fai**s**ant".

3.1. In monolinguals

Behaviorally, cross-linguistic evidence in monolinguals shows that learning to read in deep orthography takes more time and more effort than in a shallow orthography, and that it also exacerbates potential reading difficulties (Landerl et al., 2012; Landerl, Wimmer, and Frith, 2007; Schmalz et al., 2015 for a review; Seymour, Aro, and Erskine, 2003). To explain these observations, the psychological grain size theory (Ziegler & Goswami, 2005) proposed that the size of the units on which the lexical representations are built in a language correlates with the depth of the orthography: the deeper the orthography, the larger the units (multi-letter clusters, whole words) that will be used for phonological decoding and for building up orthographic lexical representations. The psychological grain size theory is explicitly framed through a phonological view of reading: it proposes that orthographic-specific parameters trigger mechanisms that affect the nature of phonological decoding strategies through the phonological grain size of processing. The psychological grain size theory goes hand in hand with the orthographic depth hypothesis (Frost, Katz, and Bentin, 1987) which specifically predicts that readers of deep orthography will rely more on *lexical phonology* than readers in shallow languages.

Accordingly, studies showed that readers of shallow orthographies rely heavily on sub-lexical reading strategies (through the reliance on phonemic recoding), whereas readers of deep orthographies should benefit from the use of larger phonological grain strategies (e.g., through the access of rimes or the lexicon) to decode irregular and inconsistent orthographic chunks present in their language (Ellis & Hooper, 2001; Frost et al., 1987; Rau, Moll, Snowling, and Landerl, 2014; Katz & Feldman, 1983; Seymour et al., 2003).

These fundamental differences on the orthographic structure of written alphabetic systems have been linked to functional variations in the underlying brain circuits, despite the fact that the brain circuits for reading are the same across languages. Paulesu et al. (2000) reported that although both Italian (shallow) and English (deep) readers recruited leftlateralized areas of the dorsal and ventral reading pathways, readers of the shallow orthography more strongly activated areas of the dorsal reading pathway compared to their peers, and readers of the deep orthography showed the opposite pattern (i.e., more activation in the ventral pathway). Therefore, it is reasonable to expect cross-linguistic differences driven by orthographic depth factors to emerge on the degree to which certain brain regions are taxed whilst reading, but also on the dysfunction severity of certain brain regions compared to others in dyslexia (Hadzibeganovic et al., 2010; Richlan, 2014; but see Paulesu et al., 2001). In line with this idea, higher recruitment of the left inferior parietal lobule may be found in shallow compared to deep orthographies (Richlan, 2014) because of the heavier use of phonological decoding strategies in the former writing systems (Ellis and Hooper, 2001; Goswami, Gombert, and Fraca de Barrera, 1998; Seymour et al., 2003). Therefore, a dysfunction of this area in dyslexia may be exacerbated in readers of shallow compared to deep orthographies.

3.2. In bilinguals

Several studies have tried to characterize the impact of orthographic depth on the manifestations of reading skills in both languages of bilingual individuals. Overall, scientific evidence converges towards similar cross-linguistic effects as those reported in monolinguals, and shows that the use of certain reading strategies depends on processing demands imposed by the orthographic structure of the language. Interestingly, these studies evaluate the reading skills of the *same* participants in two orthographies, and avoid methodological and cultural obstacles faced by cross-linguistic studies that compare different groups of individuals in different countries. Thus, they are very adequate to test hypotheses related to orthographic depth provided that proficiency and reading levels in the two languages are comparable. (Frost, 1994; Wydell & Butterworth, 1999; Ziegler & Goswami, 2005).

The reading performance of French-Spanish bilingual children with and without dyslexia was evaluated in both their deep (French) and shallow (Spanish) orthographies (Lallier, Valdois, Lassus-Sangosse, Prado, and Kandel, 2014). These children were early bilinguals, proficient in their two languages, and had learned to read in both of their languages simultaneously. Bilingual children were more accurate at reading in their shallow orthography than in their deep one, and accuracy deficits of bilingual dyslexic children were more severe in French than Spanish tasks. Moreover, the results pointed towards a preferred small grain reading strategy in Spanish compared to French: the bilingual skilled reader children used both large and small grain strategies to read accurately in French, illustrated by the presence of an advantage to read words over pseudowords. However, both types of items were read as accurately in Spanish, suggesting the use of similar small grain strategies. In our view, variations in lexicality effects reflect modulations taking place in the lexicon, and the impact of orthographic depth on lexicality effects suggest that bilinguals rely more on the lexicon when they read in their deep compared to their shallow orthography. It is worth mentioning here that such results have to be taken with caution since there was a significant lexical effect found on Spanish reading RTs in both skilled and dyslexic readers. This suggests that children somehow used two different reading strategies in their shallow Spanish orthography. In addition, the lack of lexicality effect on reading accuracy in Spanish might have reflected a ceiling effect, especially so in skilled readers (see Table 2 page 1182 of Lallier et al., 2014). Therefore, the discrepancy between accuracy and speed measures does not support entirely the hypothesis of the modulation of the reading grain size by orthographic depth factors. We will address this point more deeply in section 5.1. More striking and convincing evidence coming from this same study is the presence of accuracy deficits in the dyslexic children on a Spanish task that *necessarily* required the use of lexical, larger grain, strategies (lexical orthographic choice task: picking the correct orthographic item between a word and its pseudo-homophone, e.g., vaca-baca, llave-yave), whereas they showed no difficulties on tasks that did not (i.e., text, word, and pseudoword reading). Other work was conducted in bilingual children learning to read simultaneously in alphabetic orthographies with distinct scripts[2] (Hebrew or Persian, and English). Again, these studies drew the same conclusions: bilinguals were generally faster at learning to read in their shallow than their deep orthography (Geva & Siegel, 2000; Gholamain & Geva,1999).

These consistent effects reported in bilinguals are supported by some neuroimaging evidence. Oliver, Carreiras, and Paz-alonso (2016) assessed two groups of proficient bilinguals sharing the same L1 (Spanish) but differing in the orthographic depth of their L2 (Basque, shallow; English, deep). When the participants read in their L2, the authors reported a functional co-activation of the left vOT cortex and (i) regions of the ventral pathway for Spanish-English bilinguals, and (ii) regions along the dorsal pathway in Spanish-Basque bilinguals. Lastly, Buetler, de León Rodriguez, Laganaro, Müri, Spierer, and Annoni (2014) elegantly showed that the topography of evoked potentials reflected the use of distinct brain networks for decoding the same pseudowords either in a French (deep) or a German (shallow) context in highly proficient bilinguals. The authors showed that reading a pseudoword in a shallow German context engaged frontal phonological areas involved in sub-lexical decoding to a greater extent than reading the same pseudoword (by the same bilinagual participants) in a deep French context. In addition, pseudoword decoding engaged visuo-attentional parietal areas more strongly in the French compared to the German context, suggesting a weaker reliance on sub-lexical strategies in the deep compared to the shallow orthography of the bilingual participants (see also see also Buetler et al., 2015).

4. The impact of orthographic depth on the auditory and visual grain size

[2] Note that this may have added an additional confounding visual factor in the results.

What about the impact on cross-linguistic variations in bilinguals on the auditory and visual grain size, i.e., when performing tasks that do not engage reading *per se*? In other words, do cross-linguistic variations also affect auditory phonology and visual attention span skills? Both phonological decoding and whole-word reading strategies require the contribution of auditory and visual processes (Zoubrinetzky, Bielle, and Valdois 2014), but via different grain size: the latter strategy particularly taxes the system's sensitivity to small auditory and visual grains (single element units), whereas the former would rely on larger grains (multi-element chunks). Consequently, it is reasonable to assume that optimal grain sizes for auditory phonological processing and visual attention span also vary as a function of orthographic depth. For example, shallow grapheme-to-phoneme relationships enhance the awareness of the smallest sounds of language - the phonemes - (Hanley, Masterson, Spence,r and Evans, 2004; Mann & Wimmer, 2002) because of the reciprocal positive interactions that exist between phoneme awareness and reading development, i.e., the better the reading, the higher the phonemic awareness skills (Bialystok, Majumder, and Martin, 2003; Castle & Coltheart, 2004; Morais, Cary, Alegria, and Bertelson, 1979). Therefore, learning to read in a shallow orthography should promote the development of auditory *phonemic* processing skills. Orthographic depth should also modulate the size of the visual grain used to parse multi-letter strings (Ans, Carbonnel, and Valdois, 1998; Perry et al., 2010). In fact, learning to read in a deep orthography such as English might boost the use of large visual grain strategies to overcome difficulties coming from complex and irregular letter-to-sound mappings. Graphemes are more likely to be composed of multiple adjacent letters that have to be processed together in order to access the right phoneme. For example, it will be more efficient to memorize the visual chunk "ch" together with the whole word context "yacht" rather than on its own, in order to access its phonology. Therefore, learning to read in a deep orthography should force a wider deployment of visual attention span resources than in shallow orthographies, for which the use of simple letter-to-sound units mapping leads to accurate reading.

4.1. In monolinguals

Cross-linguistic studies in monolingual children confirmed the hypothesis of an advantage of individuals learning to read in shallow orthographies on phonemic processing skills, especially on phonemic awareness (Goswami, Ziegler, and Richardson, 2005; Patel, Snowling, and de Jong, 2004). Large-scale cross-linguistic studies also show that the contribution of phonological awareness is more important in deep than in shallow orthographies (Vaessen et al., 2010; Ziegler et al., 2010; but see Caravolas, Volín, and Hulme, 2005) and that the phonological deficits of dyslexic individuals are more severe (Landerl et al., 2012). With regards to neuroimaging evidence, the study of Paulesu et al. (2000) showed higher engagement of phonological brain regions (left superior temporal gyrus) in shallow compared to deep orthographies, which could be in accordance with enhanced and facilitated phonological processes in the former orthographies. However, no cross-linguistic differences were highlighted regarding the dysfunction of such region for dyslexic readers of shallow compared to deep orthographies (Paulesu et al., 2001).

The available cross-linguistic evidence in favor of a larger visual grain in deep than shallow orthographies is scarce. Rau et al (2014) recently used eye tracking measures to show different graphemic parsing strategies between English (deep) and German (shallow) children when reading in their native language. These results were interpreted as the necessity of English readers to parse larger orthographic sequences than German readers, i.e., a higher number of letters attended during reading. Regarding visual attention span skills, Awadh, Phénix, Antzaka, Lallier, Carreiras, and Valdois (2016) conducted a cross-linguistic study in skilled reader adults that did not reveal any difference in the number of visual elements processed simultaneously within a multi-element array between Spanish (shallow) and French (deep). However, visual attention span skills did not correlate with reading skills in Spanish whereas it did in French, suggesting a stronger contribution of the visual attention span to reading in deep orthographies (but see Lallier et al., 2014, in children). Studies quantifying cross-linguistic developmental differences on the brain network supporting visual attention span skills should shed further light on these data.

4.2. In bilinguals

Bilingual studies generally confirm monolingual cross-linguistic findings. Lallier et al. (2014) showed that French-Spanish bilingual children exhibited overall better phonemic awareness skills in their shallow orthography compared to their deep language. Similarly, Bialystok et al. (2003) reported that French-English bilingual children performed better in the French than the English language phonological task (French is considered less phonologically complex than English). In contrast, results in dyslexic bilinguals support the absence of any modulation of the phonological performance based on orthographic depth (presence of a deficit; Lallier et al., 2014; or absence of deficit: Valdois et al., 2014). It may be the case that bilingual dyslexic children do not benefit from shallow letter-to-sound conversions if an underlying primary phonological deficit causes a deficient decoding procedure. In terms of the visual grain size, de Léon Rodríguez et al. (2015) reported that the location of the first fixation over words produced by early French-German bilingual children was closer to the beginning of words when reading in German (shallow) compared to when reading in French (deep). These results suggest that bilinguals might distribute their visual attentional resources over words less widely (following a small grain strategy) in their shallow orthography than in their deep orthography.

Cross-linguistic neuroimaging studies looking at phonological processing in bilinguals offer a less clear picture. For example, Meschyan and Fernandez (2006)'s findings in Spanish-English bilinguals support Paulesu et al. (2000)'s study, showing a stronger involvement of phonological areas for shallow than deep orthographies when reading. Contrastively, Jamal, Piche, Napoliello, Perfetti, and Eden (2012) reported that proficient bilingual readers of English and Spanish relied more heavily on phonologically-related areas in their deep than shallow orthography, because of a greater phonological load imposed by the deep English orthography. These discrepancies may be linked to variations in the degree of overlap between the phonemic repertoires and the grapheme-to-phoneme conversion rules of the languages learned by bilinguals. Variations on these phonological dimensions could differentially influence the activation of phonological brain areas in reading and reading-related tasks in bilinguals (Lallier, Acha, and Carreiras, 2015).

5. Cross-linguistic transfer in bilinguals: the grain size accommodation hypothesis.

The aforementioned behavioral and neural evidence for orthographic-specific influence on the cognitive and neural reading networks indicates that bilingual individuals can adapt their resources to the orthographic properties of the targeted language. This reflects the high plasticity and flexibility of the neural and cognitive systems of these individuals. This also suggests that any cross-linguistic transfer happening between the languages of bilinguals should be shaped and driven by these cross-linguistic variations.

How can cross-linguistic transfer in bilinguals be quantified? Classically, evidence for transfer from one language to the other is provided by correlation and regression analyses that measure the relationships between processes in the two languages (e.g., Genesee, Geva, Dressler, and Kamil, 2006; Saiegh-Haddad & Geva, 2010). However, these studies alone cannot determine whether this transfer has either positive or negative consequences, whereas comparing the performance of bilinguals against monolinguals or other groups of bilinguals can. This is of critical importance especially when one wants to determine the pros and cons of learning to read in two languages on the development of these skills and their cognitive and neural underpinnings.

Our logic relies on the fact that the simultaneous reading acquisition in two alphabetic writing systems will generate cognitive and neural accommodation[3] for reading development that will further depend on deviations of the two languages on their orthographic depth. In particular, reading acquisition in two languages should prompt the use of a grain size that results from this accommodation process. We hypothesize that a *cross-linguistic blending* occurs between the preferred grain size triggered by each orthography. In other words, the preferred resulting reading strategies (i.e., serial decoding-“like” and whole word lexical reading-“like”) and cognitive resources (auditory phonology and visual attention span) would depend on a hybrid grain size between those that monolinguals would use in similar situations (see Figure 2).

[3] Our hypothesis is in accordance with some aspects of the system accommodation hypothesis (Perfetti and Liu, 2005; Perfetti, Liu, Fiez, Nelson, Bolger and Tan, 2007), that has been proposed to explain sequential bilingual reading acquisition in *different writing systems* (such as English and Korean) mostly varying on both their orthography (alphabetic versus syllabic or logographic) and scripts (visual appearance of the writing system). The accomodation hypothesis predicts that when reading is acquired in a new writing system, L2 reading procedures (and neural underpinnings) should be assimilated to those used in L1. However, when the writing systems are dissimilar enough (like Chinese and English), the reading network is assumed to accommodate to develop new neural and cognitive resources necessary to read in L2.

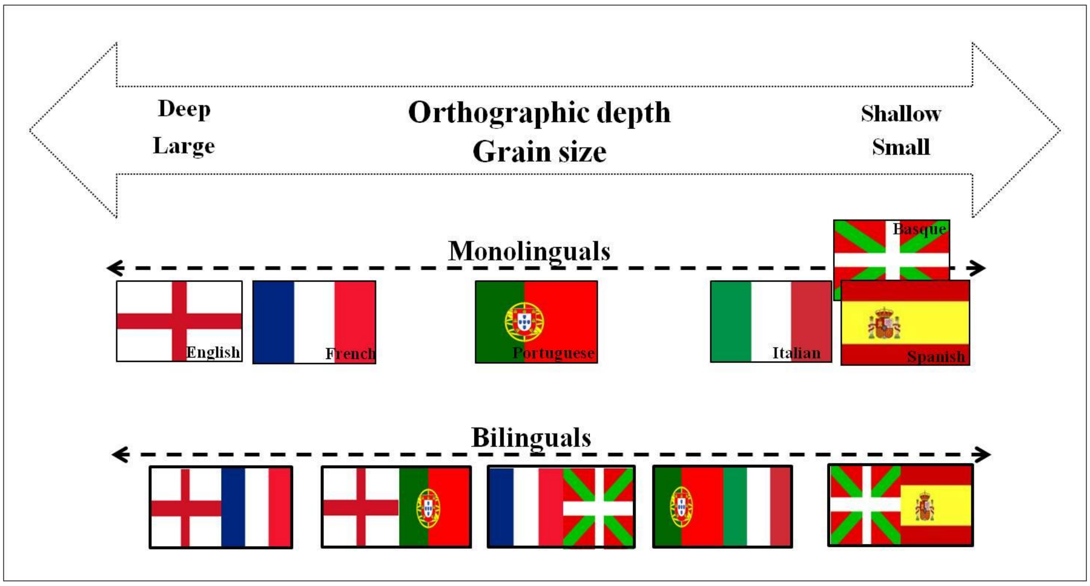

Figure 2. Illustration of the grain size accommodation hypothesis based on orthographic depth factors in simultaneous bilinguals reading in two alphabetic orthographies. The grain size used by bilingual readers would correspond to a hybrid grain size that results from monolingual reading strategies prompted by these orthographies.

5.1. Predictions of the grain size accommodation hypothesis

Importantly, the grain size accommodation hypothesis allows us to *a priori* predict the *direction of group differences* that should be observed, based on the orthographic properties of the language(s) learned. We predict that bilingual readers who acquire reading in a deep orthography in addition to a shallow orthography should rely on smaller grains (e.g., over-reliance on sub-lexical strategies and reduced lexical effects in reading) in their deep orthography as compared to the grains used by monolinguals in this same deep language. Conversely, the same bilingual readers should use larger grains in their shallow orthography (e.g., greater lexical effects in reading, wider visual attention span deployment) than monolinguals reading in this same shallow orthography.

These predictions can be tested through the use of classical tasks and between-group designs involving the comparison of monolinguals *versus* bilinguals on their common language (i.e., French-Spanish bilinguals *versus* Spanish monolinguals on Spanish), or of a bilingual group *versus* another bilingual group on their common language (i.e., Spanish-Basque bilinguals *versus* Spanish-French bilinguals on Spanish). Below, we propose possible experiments that would allow testing our predictions in bilinguals with regards to the grain size used in reading, the auditory phonological grain size, and the visual grain size.

First, we propose that the size of lexical effects in naming or lexical decision tasks (speed and/or accuracy) could indicate the relative difference between the preferred grain size used for reading lexical and non-lexical orthographic items (see Lallier et al., 2014; Lallier et al., 2015). For example, larger lexical effects for French-Spanish bilinguals compared to Spanish monolinguals in Spanish should reflect a greater reliance on the lexical procedure (and on larger grains) in the bilingual group because of the accommodation processes resulting from knowing how to read in the deep French orthography. Following the same reasoning, smaller lexical effects for Spanish-Basque bilinguals compared to Spanish-French bilinguals in Spanish would be expected. These specific predictions should also be assessed through neuroimaging designs: in particular, the effective connectivity between the regions of the reading network should be a good estimate of the degree of reliance on the dorsal (sub-lexical, small grain) and the ventral (lexical, large grain) reading pathways whilst reading different types of items (e.g., see the method used by Levy et al., 2009).

It is important to keep in mind that orthographic depth modulations of lexical effects in reading might not *necessarily* be the same for accuracy and speed measures. For example, Lallier et al (2014) in Spanish-French bilinguals reported a lexical effect on reading speed but not on reading accuracy in Spanish whereas similar lexical effects were found on speed and accuracy in French. Interestingly, reading speed was strongly linked to visual attention span skills whereas reading accuracy was only linked to phonemic awareness skills (see Figures 1-4 of Lallier et al., 2014). We argue that such findings support the use of different visual and phonological grain sizes (preferentially affecting reading speed and accuracy, respectively) in the same individuals when reading in their shallow orthography. Figure 5 illustrates how orthographic depth factors may partly determine whether large visual grain strategies are accompanied by large phonological grain strategies, and may modulate lexical effects on speed and accuracy measures in the same individuals.

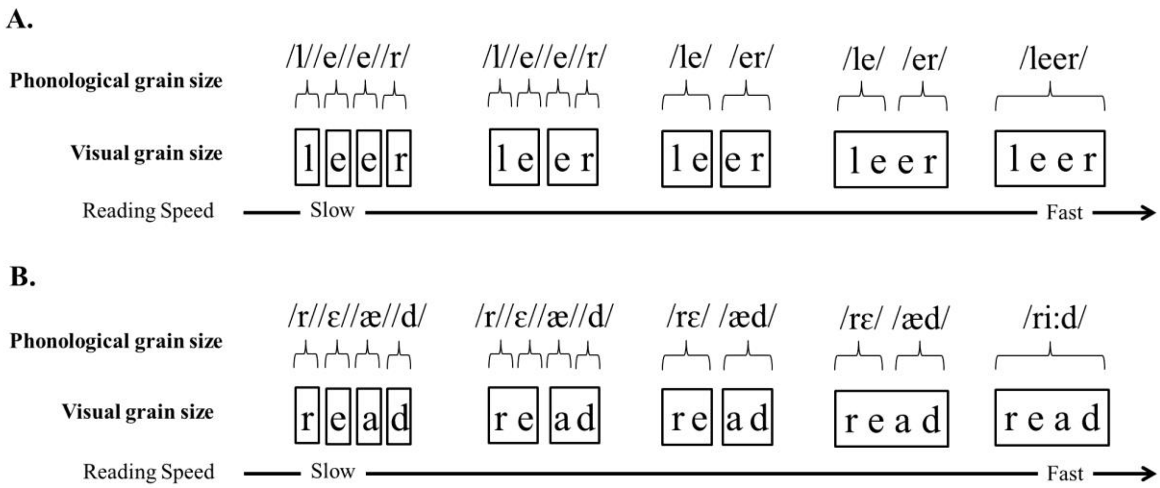

Figure 5. Illustration of a non-exhaustive series of possible combinations between the visual grain size (size of the black squares) and the phonological grain (size of the braces) accessed from print by individuals reading the word “leer” in Spanish (A.) and “(to) read” English (B.). From left to right: visual and phonological small grain combinations simulate decoding-like strategies whereas large grain combinations simulate lexical reading. The visual grain size determines reading speed in both the shallow (A.) and the deep (B.) orthographies, whereas the phonological grain size determines reading accuracy in the deep orthography only. In Spanish, any phonological grain size strategies leads to accurate reading if the correct grapheme-to-phoneme conversion rules are applied. In English, the use of both large visual and phonological grains is necessary to read accurately and solve complex grapheme-to-phoneme mappings (e.g., rightmost situation in B.).

It has been previously shown that, for both shallow and deep orthographies, the larger the visual attention span skills, the faster the reading speed (Lallier et al., 2014; Lobier, Dubois, and Valdois, 2013), showing that when several letters are identified simultaneously in one visual attentional capture, the following reading computations are speeded-up (e.g., phonological access from print). Therefore, lexical effects on reading speed may be expected across orthographies (see Figure 5). We predict a different picture for reading accuracy. In shallow orthographies (Figure 5. A.), letters identified simultaneously through a large visual grain could be converted through a phoneme-by-phoneme strategy, or through the access of rimes or phonological lexical representations. In fact, the use of any phonological grain size would similarly lead to accurate words and pseudowords reading regardless of the visual grain size used: in this case, an absence of lexical effect on accuracy is predicted. In deep orthographies (Figure 5. B.), the use of large phonological grains should often accompany the use of large visual grains because in most cases, accessing rimes or whole word phonological units constrains reading accuracy. In that case, lexical effects on both speed and accuracy are expected (See Figure 5. B). Overall, in order to avoid the report of inconsistent findings across studies (e.g. Schmalz, Robidoux, Castles, Coltheart, and Marinus, 2017), future studies attempting to test our predictions in bilinguals through lexical effects in reading should systematically take into account both accuracy and speed measures in relation to phonological and visual grain sizes.

Second, predictions on the auditory phonological grain size could be easily tested with tasks tapping into phonemic awareness, such as deleting the first phoneme of pseudowords presented auditorily, or segmenting pseudowords into their constituting phonemes. For example, we expect larger phonological grain size strategies to result in a greater number of deletion errors like first syllable or onset deletion (i.e., /platu/ segmented as /pla//tu/ or /pl//atu/ instead of /p//latu/). At the brain level, a stronger bias to the left auditory cortex may be found in response to phonological items for individuals highly sensitive to phonemic details compared to individuals who rely more on larger phonological units such as syllables (Lizarazu et al., 2015; Molinaro, Lizarazu, Lallier, Bourguignon, and Carreiras, 2016; Poeppel, 2003).

Third, accommodation processes on the visual grain size could be measured through the visual attention span skills of participants: a wider visual attention span deployment (i.e., a higher numbers of visual elements identified simultaneously) and a stronger contribution of these skills to reading is expected if individuals rely on large visual grain strategies. At the brain level, a strong engagement of the superior parietal lobule whilst performing reading or reading related tasks should reflect higher visual attention span skills demands and the use of larger visual grain strategies. Lastly, eye movements could also be informative (see de León Rodríguez et al., 2015). For example, the distance between the location of the first fixation over words or pseudowords and the beginning of the items might be another index of the size of the visual grain used, such that the further the first fixation from the beginning of items, the larger the visual grain used.

5.2. Behavioural and ERP evidence supporting the grain size accommodation hypothesis so far.

The following section will present studies conducted on simultaneous bilingual populations that directly support the grain size accommodation hypothesis (see Figure 2). These studies have compared either different groups of bilinguals against each other or bilinguals against monolinguals on the same language, in order to assess whether bilingualism *per se* has positive outcomes on reading and reading-related skills in alphabetic languages or whether this depends on specificities of the orthography between the two languages.

In a first study, Lallier et al. (2015) evaluated bilingual children attending Grade 2 and Grade 5 in the French-Basque bilingual region and the Spanish-Basque bilingual region of the Basque Country. A series of tasks were administered *in Basque* (a shallow orthography) to all children including a phonemic deletion task, an adaptation of the partial report task (measuring the visual attention span), and a list of Basque word and pseudoword reading. Importantly, all children were matched for their linguistic proficiency and use of Basque and of the other language (French or Spanish). The four bilingual groups were characterized as early proficient simultaneous bilinguals. Therefore, evaluating these groups offered us an exceptional opportunity to quantify the impact of the orthographic properties of a deep and a shallow orthography on reading acquisition in another orthography (Basque). The results showed that first, the Spanish-Basque bilinguals made fewer errors when reading Basque pseudowords than the French-Basque bilinguals independently of the Grade. This group difference was observed only in the most difficult condition, i.e., on improbable pseudowords that did not respect Basque orthotactics (see Figure 3). The authors proposed that the deeper encoding of the links between letters and sounds in Spanish-Basque bilinguals (knowing two shallow orthographies) sharpened small grain decoding strategies in Basque. Moreover, auditory phonemic processing was also enhanced in these same children since the Spanish-Basque bilinguals outperformed their French speaking peers on the most difficult condition of the Basque phonemic deletion task - deleting the first phoneme of a CCV phonological cluster. Therefore, as hypothesized, different grain size in the two groups were automatically used, in particular in *difficult* situations of Basque processing. Lastly, results on visual attention span skills suggested that fewer visual units from a 5-letter array presented briefly (200 ms) were salient for Spanish speaking children in Grade 2 compared to their French speaking peers. This difference disappeared at Grade 5. As predicted, this illustrated that learning to read in a deep orthography in addition to a shallow one boosts from early on the homogenous deployment of visual attention over orthographic strings. This hypothesis was also supported by the fact that at both grades, French-Basque bilinguals demonstrated a word familiarity advantage over pseudowords (potentially stemming from the use of large grain strategies) on Basque reading accuracy, while Spanish-Basque bilinguals read both types of item with similar accuracy. Moreover, this was observed only in challenging reading, i.e., improbable words and pseudowords that did not respect Basque orthotactic rules (see Figure 3).

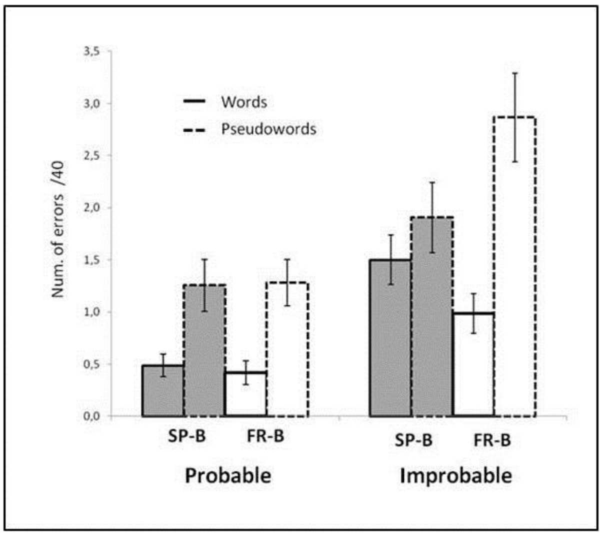

Figure 3. Performance on Basque single item reading in the Spanish-Basque bilinguals (grey bars; SP-B) and the French-Basque bilinguals (white bars; FR-B). Standard error bars are depicted. *From Lallier et al., 2015.*

At this stage, it is important to point out that the interpretation of the data from Lallier et al. (2015) should be presented with caution: Spanish and Basque share most of their phonemic categories, as well as their grapheme-to-phoneme mapping rules whereas French and Basque do not. In order to rule out any phonological distance effect on the results obtained, it is important to test and confirm our hypothesis in bilinguals knowing one deep and one shallow orthographies that overlap minimally in terms of phonemic repertoires, and grapheme-to-phoneme conversion rules. This is the case of Welsh and English. Lallier, Carreiras, Tainturier, Savill, and Thierry (2013) asked English monolingual and early Welsh (shallow)-English bilingual reader adults to report whether or not a target letter displayed at fixation was present in either a nonword (consonant string) or an English word presented immediately before (for 180 ms). Event-related brain potentials (ERPs) were simultaneously recorded. For word and nonword probe trials, behavioural performance was overall unaffected by target letter position in the probe (being at ceiling for word probes), suggesting similarly orthographic encoding in the two groups. In contrast, the amplitude of ERPs locked to the target letters (P3b, 340-570ms post target onset) were differently modulated by the position of the target letter in words and nonwords between bilinguals and monolinguals. P3b results show that bilinguals who learnt to read simultaneously in a deep and a shallow orthographies encoded English orthographic information presented to the right of fixation more poorly than monolinguals, reflecting, here again, a narrower mode of visual attention distribution potentially due to the acquisition of a shallow orthography. Importantly, this study also suggests that group effects that may be hidden by ceiling effects observed behaviourally can be revealed using more sensitive measures such as ERPs.

The results of the last two studies support the grain size accommodation hypothesis in bilingual groups whose languages share or not their phonemic repertoires and grapheme-to-phoneme conversion rules. However, they cannot address the question as to whether similar effects would persist when the languages of bilinguals do not share the same alphabet. In fact, one may hypothesize that having to learn two scripts and two sets of visual symbols may override the manifestations of grain size accommodation. The study of Bialystok, Luk, and Kwan (2005) suggests the opposite. These authors compared the decoding and phonological awareness skills of groups of Grade 1 children speaking and learning to read in English and another shallow alphabetic language that could either share the same script as English

(Spanish) or not (Hebrew). Importantly, these two bilingual groups were also compared to a group of monolingual English children. The authors showed that children who had learnt a shallow orthography in addition to English outperformed their English monolingual peers on phonemic awareness (phoneme counting task). In the case of pseudoword decoding, the authors showed that the Hebrew-English bilinguals significantly outperformed their English monolingual peers (note that the Spanish speaking children exhibited better scores than the English monolinguals although this difference was not significant). Overall, these results speaks in favor of a phonological processing advantage (i.e., on phonemic awareness and on phonological decoding) for beginner bilingual readers knowing a shallow orthography in addition to English, regardless of whether the two languages share the same alphabet or not.

Taken together, these studies shed light on how cross-linguistic transfer driven by orthography-specific factors constrains both the phonological and visual grain size underlying oral and written language processing in bilinguals. In particular, learning to read in a shallow orthography in addition to a deep orthography may result in an advantage for the development of phonemic awareness that would help overcoming phonologically challenging processing situations. However, it may be a slight disadvantage compared to learning to read only in a deep orthography, when the reading situation requires spreading visual attention resources widely over the letter string. Would these effects affect similarly the symptoms of bilingual dyslexia? Lallier, Barr, Thierry, Carreiras, and Tainturier (Unpublished results) offer preliminary hints on how bilingualism and cross-linguistic transfer can affect positively or negatively the manifestations of reading disorders, depending on orthographic-specific features of the language learned (see also Abu Rabia & Siegel, 2002; Dafontura & Siegel, 1995). The authors assessed a group of 15 Welsh-English bilingual adults with dyslexia and a group of 15 English monolingual adults with dyslexia, and compared their performance on words and pseudoword reading, as well as visual attention span and phonemic awareness *in*

English, to a group of 30 age-matched skilled readers composed of both bilinguals and monolinguals. Importantly, the two dyslexic groups showed similar global poor reading level in English. The results revealed a benefit of learning to read in a shallow orthography (Welsh) in addition to English on the manifestations of dyslexia only on literacy tasks engaging a high degree of phonological processing, such as spelling. Welsh-English dyslexic bilinguals also exhibited weaker lexicality effects compared to English monolingual dyslexic participants, which might eventually have affected the build-up of lexical orthographic knowledge. Again, this data suggests that learning to read in a shallow orthography in addition to English might narrow down the grain size for performing literacy tasks in English.

5.3. Challenges faced by the grain size accommodation hypothesis

Factors independent from orthographic depth (and from the overlap in phonological repertoires and scripts) might modulate the use of some *preferred* or *optimal* grain size compared to others.

For example, small grain strategies are extremely important for acquiring reading at early developmental stages, whereas large grain ones might be equally important across development (Bosse & Valdois, 2009; Ziegler et al., 2014). Moreover, item familiarity may impose some constraints on size of the grain use to read: unfamiliar and infrequent words are likely to engage decoding and small grain strategies, while familiar and frequent word reading is prone to rely on lexical and large grain strategies. We expect cross-linguistic transfer based on orthographic depth factors to also undertake modulations driven by the processing demands of the reading situation itself. This is illustrated in Figure 4. In particular, longitudinal studies in bilinguals before and after learning to read should be highly valuable to determine whether and how much cross-linguistic transfer and grain size accommodation processes vary across development, whilst taking into account the nature of the items read.

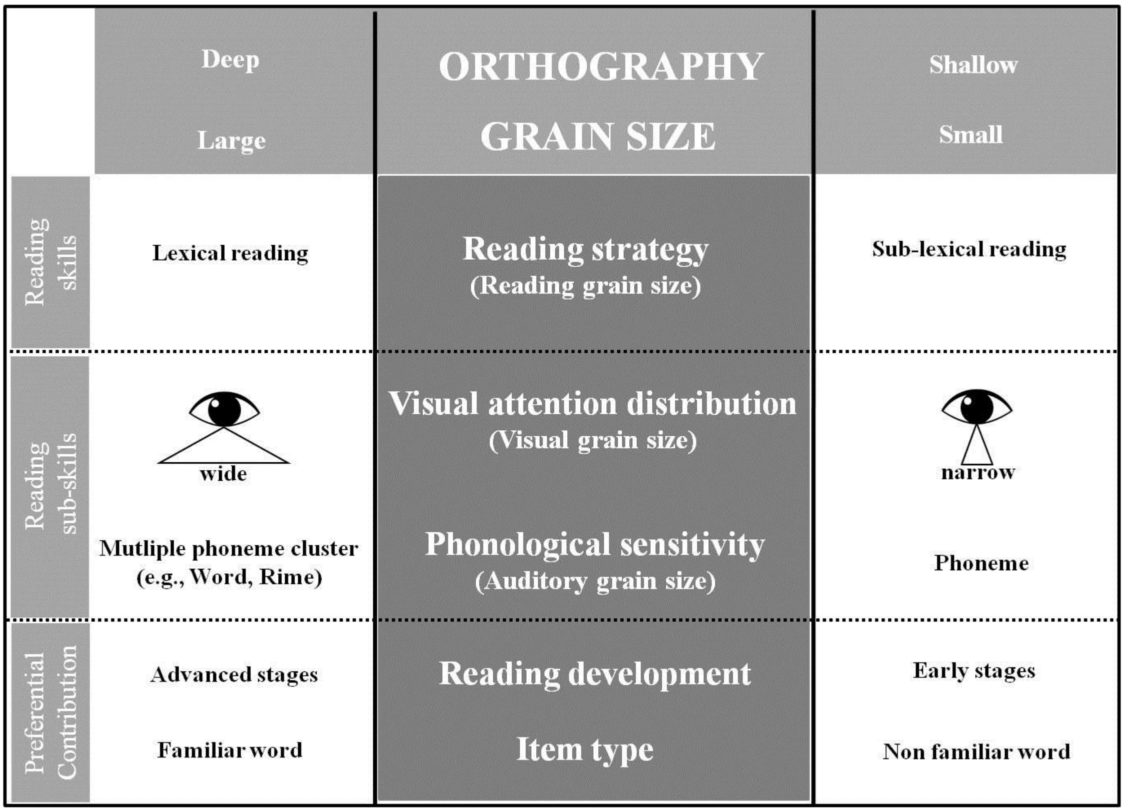

Figure 4. Illustration of the orthographic depth effects on the grain size used for performing reading tasks (i.e., reading skills) and reading related cognitive tasks (i.e., reading sub-skills), as well as the reading situations in which these orthographic-specific variations might contribute preferentially.

In addition to the level of reading expertise (see Figure 4), grain size accommodation processes may also fluctuate depending on linguistic proficiency (de León Rodríguez et al., 2016). We foresee that the development of hybrid strategies described in the presentation of our hypothesis may especially thrive when reading is *simultaneously* acquired in two orthographies (i.e., early simultaneous bilinguals). In this particular case, immature cognitive and neural reading networks would be ready to integrate and accommodate to all linguistic orthographic experiences with an equivalent pre-disposition for deep and shallow inputs. This would result in reading strategies generated and self-taught from both deep and shallow orthographic environments. The studies presented here were conducted in early highly proficient simultaneous bilinguals. Future studies should also evaluate the present framework in late low proficient sequential bilinguals in order to refine the grain size accommodation hypothesis.

Last (but not least), we hope that the scope of the present hypothesis will eventually broaden to bilingual reading acquisition in non-alphabetic languages, as well as in individuals who master more than two languages, since a large proportion of the worldwide population falls within these categories.

6. Conclusions

The data presented throughout this article point towards the existence of orthographic-specific influences and cross-linguistic interactions on reading in bilinguals learning to read (children) or having learned to read (adults) in two alphabetic orthographies simultaneously. We report consistent results on the nature of the modulations of cross-linguistic transfer on the typical and atypical reading development in various groups of bilinguals. More particularly, these results show that the phonological and visual grain size used for reading and performing reading-related tasks are subject to accommodation processes driven by the orthographic properties of both the languages of bilinguals. Importantly, we identified a number of factors that might influence the outcomes of studies assessing the grain size accommodation hypothesis in bilinguals, e.g., the scripts and phonological distance between the two languages of bilinguals, the language(s) proficiency, the developmental stage, the type of item presented. Future studies will put effort in determining the behavioral and neural (structural and functional) fingerprints of cross-linguistic accommodation based on orthographic depth, and their modulation by these additional factors. Lastly, since orthographic depth prompts the use of distinct cognitive strategies for reaching similar goals (i.e., reading), some specific language pairs may (more than others) offer the opportunity to compensate reading and cognitive difficulties in bilingual dyslexic individuals. Therefore, practical questions are open on the power of positive cross-linguistic transfer in bilingualism for developing evidence-based reading teaching methods and remediation programs in bilinguals learning to read in two orthographies simultaneously.

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