Lateralized reading in the healthy brain: a behavioral and computational study on the nature of the visual field effect.

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Abstract

Despite its widespread use to measure functional lateralization of language in healthy subjects, the neurocognitive bases of the visual field effect in lateralized reading are still debated. Crucially, the lack of knowledge on the nature of the visual field effect is accompanied by a lack of knowledge on the relative impact of psycholinguistic factors on its measurement, thus potentially casting doubts on its validity as a functional laterality measure. In this study, an eye-tracking-controlled tachistoscopic lateralized lexical decision task (Experiment 1) was administered to 60 right-handed and 60 left-handed volunteers and word length, orthographic neighborhood, word frequency, and imageability were manipulated. The magnitude of visual field effect was bigger in right-handed than in left-handed participants. Across the whole sample, a visual field-by-frequency interaction was observed, whereby a comparatively smaller effect of word frequency was detected in the left visual field/right hemisphere (LVF/RH) than in the right visual field/left hemisphere (RVF/LH). In a subsequent computational study (Experiment 2), efficient (LH) and inefficient (RH) activation of lexical orthographic nodes was modelled by means of the Naïve Discriminative Learning approach. Computational data simulated the effect of visual field and its interaction with frequency observed in the Experiment 1. Data suggest that the visual field effect can be biased by word frequency. Less distinctive connections between orthographic cues and lexical/semantic output units in the RH than in the LH can account for the emergence of the visual field effect and its interaction with word frequency. Remarkably, the size of the interaction between the visual field effect and word frequency did not differ in the two hand preference groups, suggesting that psycholinguistic factors don't hamper the measurement of interindividual differences in the functional lateralization of language.

1. Introduction

The term “visual field effect” in lateralized reading refers to the observation that - in divided visual field presentation paradigms - words presented to the right visual field (RVF) are typically processed faster and more accurately than words presented to the left visual field (LVF). This phenomenon was reported by Mortimer Mishkin in his M.A. thesis at McGill University (1949), in a set of experiments aiming to explore the effect of retinal locus on word recognition in healthy subjects (see also Mishkin & Forgays, 1952). The methodological core of divided visual field reading paradigms is the combination of lateral visual stimulation (i.e., letter strings are projected left or right, away from the midline) and tachistoscopic (i.e., fast) visual presentation. The first feature allows experimenters to target one hemisphere specifically, by leveraging the crossed arrangement of the visual system (stimuli presented in the LVF are first processed by the right hemisphere [RH], while stimuli presented in the RVF are first processed by the left hemisphere [LH]). Fast presentation, instead, allows experimenters to minimize the chance of eye movements. Indeed, if eyes move towards a lateralized stimulus to be optimally perceived at the center of the visual field, then the stimulus becomes potentially available to both hemispheres (for a different interpretation, see Brysbaert, 1994; Brysbaert et al., 1996; Lavidor & Walsh, 2003), thus potentially disrupting the experimental manipulation of laterality (for a methodological review, see Bourne, 2006).

The divided visual field technique became popular for the study of the lateralization of language processing in patients who underwent partial or complete commissurotomy, often referred to as “split-brain” patients (see for instance Cohen et al., 2000; Gazzaniga et al., 1962; Reuter-Lorenz & Baynes, 1992; Zaidel & Peters, 1981). In this direction, divided visual field studies on split-brain patients have suggested that, in line with classical neuropsychological data (Dejerine, 1892), the LH is typically dominant over the RH for reading (see for instance Baynes et al., 1992; Gazzaniga & Sperry, 1967). Also, in line with the seminal observation from Mishkin & Forgays (1952), the visual field effect in lateralized reading has been consistently observed in healthy participants as well (see for example Babkoff & Ben-Uriah, 1983; Chiarello et al., 1986; Chiarello et al., 2005; De Clercq & Brysbaert, 2020; Iacoboni & Zaidel, 1996; Leiber, 1976; Mergen & Kuruoglu, 2021; Tomkins, 2020; Willemin et al., 2016). For this reason, the visual field effect in lateralized reading has been massively used as a tool to measure functional hemispheric lateralization of reading, and of language in general (Gerrits et al., 2020; Hausmann et al., 2019; Hunter & Brysbaert, 2008; Van der Haegen et al., 2011). However, there is poor consensus in the literature on the neurocognitive mechanisms giving rise to the visual field effect. Such inconsistency not only constitutes a challenge for the theoretical interpretation of the visual field effect: it could also cast doubts on the quality of lateralization measures obtained through this method. Indeed, different interpretations of the origins of the visual field effect in lateralized reading can imply different relationships between the specific stimuli employed in the lateralized reading task and the magnitude of the resulting visual field effect.

1.1 Explaining the visual field effect in lateralized reading

Unlike split-brain patients, healthy subjects do not have their hemispheres structurally and functionally separated from each other. Therefore, information initially targeting the right primary visual cortex due to LVF stimulation is potentially free to flow to the LH to be processed by the dominant visual word form system. If so, then what causes stimuli projected to the LVF to be read with greater difficulty than stimuli projected to the RVF?

One proposal in this regard suggests that the RH provides no contribution at all towards lexical orthographic processing. This proposal was formalized in a model of lateralized word processing by Ellis (2004; Ellis et al., 1988). This framework initially built on evidence suggesting that the word length effect (i.e., greater processing costs for longer words) is comparatively bigger for words printed in standard, horizontal format presented to the LVF/RH than to the RVF/LH (Brysbaert & d'Ydewalle, 1990; Young & Ellis, 1985). The observation that presentation of words vertically (Young & Ellis, 1985; Bub & Lewine, 1988) made the length effect in the RVF/LH equal to that of LVF/RH and had no effect on the LVF/RH lead to the proposal that, while words presented in the RVF/LH can access the LH lexicon in a fast, parallel way, words presented in the LVF/RH have to undergo a process of extraction of abstract letter identities. According to Ellis et al. (1988; 2004), this process would be conducted in a letter-by-letter fashion, and would give rise to the word length effect. Crucially, such conversion into abstract letters would be minimally required in the RVF/LH, unless when processing words presented in an unfamiliar format. This would explain why, when words in standard horizontal format are presented, a larger word length effect can be observed in the LVF/RH than in the RVF/LH (i.e., a word length-by-visual field/hemisphere interaction), as well as why a processing cost exists in the LVF/RH relative to the RVF/LH. In line with this view, evidence of larger orthographic neighborhood effects (conceptualized as top-down influence from lexical knowledge to single-letter processing; Andrews, 1992; Coltheart & Rastle,

1994) in the LVF/RH than RVF/LH could be explained in terms of greater processing at the letter level for words projected to the LVF/RH than to the RVF/LH. Crucially, for the model proposed by Ellis et al. to hold, no assumption of lexical representations in the RH is needed: stimuli projected to both the RVF and the LVF would ultimately reach the (single) orthographic lexicon located in the LH, and the visual field effect would be explained by the necessity of extracting abstract letter identities in the LVF/RH but not in the RVF/LH. According to the model, the RH is essentially word-blind: stimuli presented to the LVF and initially targeting the RH are simply "relayed" to the LH to be processed by the dominant hemisphere (Eviatar et al., 1990; Waldie & Mosley, 2000a; Weems & Reggia, 2004). Within the present study, this framework will be defined as "*callosal relay-single LH orthographic lexicon*" model.

A different explanation towards the visual field effect in lateralized reading suggests that the visual field effect represents asymmetries in how orthographic information is stored and/or retrieved in the two cerebral hemispheres (*direct access – two orthographic lexicons* framework). Accordingly, lateralized orthographic information targeting the LVF or the RVF would primarily be processed by the RH and LH, respectively, and poor performance for stimuli targeting the LVF/RH would be due to poorer processing in the RH compared to the LH (Eviatar et al., 1990; Waldie & Mosley, 2000a; Weems & Reggia, 2004)[1]. This framework has been inspired by neuropsychological studies conducted on patients displaying damage to the neural units commonly involved in reading, following a brain lesion of the LH (i.e., patients showing Pure Alexia and patients showing Deep Dyslexia). In particular, evidence suggests that these patients often show signs of spared reading abilities (attributed to the RH compensating after LH damage), limited to high frequency and/or high-imageability words (Bonandrini et al., 2020; Coltheart, 1980, 2000; Coslett & Saffran, 1989; Coslett & Saffran, 1994; Saffran et al., 1980; Saffran & Coslett, 1998), although frequency and imageability effects in Pure Alexia are less evident than those in Deep Dyslexia. In line with this framework (see Saffran & Coslett, 1998 or Luzzatti, 2003; Luzzatti et al., 1998 for a graphical representation) the visual field effect would be due to weaker/poorer lexical orthographic representations in the RH compared to the LH, only enabling processing of highly frequent and/or highly imaginable items. Accordingly, the RH would not be completely word-blind (Zaidel, 1982; Zaidel, 1983) and performance in lateralized reading should maximally differ between the two

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[1] In this context, *direct access* should not be interpreted as *independence* of the two hemispheres (Chu et al., 2020; Chu & Meltzer, 2019; Iacoboni & Zaidel, 1996; Rauschecker et al., 2012). In this regard, Weems & Reggia (2004) have proposed a *cooperative* model, in which lateralized stimuli are primarily processed by the contralateral hemisphere, but hemispheres can interact.

visual fields/hemispheres according to variables acting at the lexical/semantic level e.g., word frequency and/or imageability.

Both the *direct access – two orthographic lexicons* and the *callosal relay – single orthographic lexicon* frameworks anticipate interactions between the visual field effect and the psycholinguistic variables affecting reading. However - *prima facie* - the predictions of the two models appear difficult to disentangle. Although the *callosal relay – single orthographic lexicon* framework anticipates interaction effects between visual field and word length and orthographic neighborhood, it does not formally exclude the possibility of interactions between visual field and frequency and/or imageability (Ellis, 2004). However, the *callosal relay – single orthographic lexicon* framework assumes the existence of just one lexical store (in the LH). Therefore, the only mechanism that would explain a different effect of frequency (or imageability) between visual fields/hemispheres would be a greater processing cost for words initially targeting the LVF/RH. Such cost - due to the extraction of abstract letter identities in the LVF/RH - should manifest itself as a greater word length effect in the LVF/RH than in the RVF/LH. In addition, if the effect of orthographic neighborhood is interpreted as top-down influence from the orthographic lexicon to extraction of abstract letter identities (Ellis, 2004), by virtue of this latter processing step being necessary in the RH and not in the LH, a greater effect of orthographic neighborhood should emerge in the LVF/RH than in the RVF/LH. In other words, the *callosal relay – single orthographic lexicon* predicts an interaction between visual field and word length as well as with orthographic neighborhood. Interaction effects with frequency and imageability could also comply with the *callosal relay – single orthographic lexicon* framework, but they should be accompanied by interactions with word length and neighborhood.

Conversely, for the *direct access – two orthographic lexicons* framework to work, the assumption of different processes for the extraction of letter identities in the two cerebral hemispheres is unnecessary. Accordingly, this model does not predict the emergence of greater length and/or orthographic neighborhood effects in the LVF/RH than in the RVF/LH. Rather, the model predicts weaker lexical representations in the RH than in the LH, and that access to the RH lexicon implies a processing cost. Therefore, in line with this model, different effects of frequency and/or imageability (that are lexical and semantic variables, respectively) are anticipated between visual fields/hemispheres even without the concurrent emergence of hemispheric differences in the effects of word length and/or orthographic neighborhood.

In this study, we will explore the relative effect of word length, orthographic neighborhood, word frequency and imageability towards the visual field effect, with the aim of providing an experimental test bed for the two theoretical accounts. In this regard, it is worthy to highlight that the theoretical contraposition between these two frameworks should not be considered as strictly dichotomous. Indeed, as recent evidence suggests (see Chu & Meltzer, 2019), *direct access* and *callosal relay* phenomena are most likely to co-exist at the neural level. The goal of the present investigation is to explore the relative contribution of *direct access* and *callosal relay* mechanisms towards the visual field effect and its interactions with psycholinguistic variables.

1.2 Lateralization of reading and psycholinguistic variables

The *direct access – two orthographic lexicons* and the *callosal relay – single orthographic lexicon* frameworks have been both adopted as functional brain models accounting for the visual field effect in divided visual field reading studies (Babkoff & Ben-Uriah, 1983; Chiarello et al., 1986; Day, 1977; De Clercq & Brysbaert, 2020; Ellis et al., 1988; Olk & Hartje, 2001; Waldie & Mosley, 2000b; Whitney & Lavidor, 2005). However, the lack of a shared functional brain model capable of explaining the visual field effect poses a possible problem for the use of divided visual field reading paradigms to measure functional hemispheric asymmetries. Indeed, while according to the *callosal relay – single orthographic lexicon model* word length and orthographic neighborhood impact the visual field effect in lateralized reading, according to the *direct access – two orthographic lexicons model*, word frequency and imageability could modulate the visual field effect in lateralized reading. The available literature is of little help in this direction, as only a handful of studies directly compared the two theoretical frameworks and results are largely inconsistent: some studies have highlighted the effect of word length and/or orthographic neighborhood (Iacoboni & Zaidel, 1996; Lavidor et al., 2001; Perea et al., 2008), some others have highlighted the effect of word frequency and/or imageability (Day, 1977), and some others reported both (Leiber, 1976).

The lack of knowledge on the functional brain model underlying the visual field effect is therefore accompanied by the lack of knowledge regarding the extent to which this effect can be qualified by the psycholinguistic properties of the stimuli. This implies that laterality measurements could be affected by psycholinguistic variables to an unknown extent. In other words, the extent to which functional laterality measures based on lateralized reading represent the effect of the specific stimuli used to conduct the measurement, rather than a proxy of more invariant properties of the functional organization of mind and brain, is -to the present day- largely unknown. In broader terms, it is worthy to acknowledge that the visual field effect captures the endpoint of a set of computations necessary to convert an input into a behavioral output, with these operations being essentially elusive to direct measurement. In this sense, a “pure measure of the visual field effect” can hardly exist. However, while the interactions between neural computations and behavior cannot be directly quantified, measurement biases of the visual field effect due to the specific stimuli adopted in each lateralized reading task can be directly accounted for at the behavioral level. Still, an extensive quantification of psycholinguistic effects on the visual field effect is not available - to the best of our knowledge - in the literature.

In addition, it is worth considering that one of the main purposes of the visual field effect as a tool to measure laterality is to identify different patterns of functional lateralization among individuals (Gerrits et al., 2020; Hausmann et al., 2019; Hunter & Brysbaert, 2008; Van der Haegen et al., 2011). In this regard, divided visual field reading paradigms have been often used to explore differences in the functional lateralization of reading between left- and right-handers. Indeed, left-handed participants have been associated with greater variability in functional lateralization patterns than right-handers[2]. As much as in right-handers, a RVF/LH advantage over the LVF/RH was observed in left-handers in lateralized reading (Waldie & Mosley, 2000b; Willemin et al., 2016), although this effect is apparently smaller in left-handers than in right-handers across studies (Kim, 1994). However, it cannot be excluded that psycholinguistic features of the stimuli could modulate the effect of functional brain lateralization on the visual field effect. It is therefore critical to explore to what extent any psycholinguistic effect on lateralized reading is consistent in groups of subjects characterized by different patterns of functional hemispheric dominance.

1.3 Modelling the “computational core” of the visual field effect

Although the predictions of the theoretical frameworks aiming to explain the visual field effect are defined at a qualitative level, they have also inspired computationally implemented models of reading. In particular, the SERIOL model (Whitney, 2001; Whitney, 2008; Whitney & Lavidor, 2005)

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[2] As far as spoken language is concerned, among right-handed individuals, 96% show LH dominance, 4% show a bilateral pattern and less than 1% show RH dominance; conversely, among left-handers 76% show LH dominance, 14% show bilateral pattern and 10% RH dominance (Pujol et al., 1999; see also Branch, Milner & Rasmussen, 1964).

represents a possible formalization of the *callosal relay – single orthographic lexicon* framework. Broadly speaking, the model delineates a hierarchical set of operations that allow the encoding of letter order for words presented centrally to be recognized. However, in doing so, it defines how the two hemispheres conduct pre-lexical processing of orthographic strings. In particular, the model describes a *retinal* level of analysis, in which in both primary visual areas the activation associated with visual input decreases as a function of distance from the central midline. Subsequently, visual features are independently extracted in each hemisphere. At this “feature level” the *acuity gradient* of the retinal level is converted into an orthography-specific *locational gradient* (e.g., in languages read from left to right this implies decreasing activation from left to right). Subsequently, the locational gradient interacts with letter nodes, giving rise to a temporal firing pattern that encodes letter position. Finally, the timing of bigrams is used to perform lexical access. According to the SERIOL model, to produce a left-to-right locational gradient, the acuity gradient would need to undergo an inversion in the LVF/RH. Such inversion would involve a delay that increases as a function of the number of letters involved. This would explain the greater effect of word length in the LVF/RH than in the RVF/LH. In addition, stronger left-to-right inhibition for the LVF/RH than for the RVF/LH at the feature level would give rise to a bigger orthographic neighborhood effect in the LVF than in the RVF.

Conversely, Weems & Reggia (2004) adopted a connectionist approach to formally compare the *callosal relay* and *direct access* models. All the models implemented by Weems & Reggia included an input layer, one or two output layers and one association (hidden) layer for each hemisphere. In all models the input layer was fully connected to both association layers simulating the two cerebral hemispheres, but the learning rate of the LH was set to be 50% higher than the RH. A *callosal relay* model was simulated by introducing strong connectivity from the RH to the LH, but minimal connectivity in the opposite direction, and allowing response output only from the LH. A *direct access* model with hemispheres independent from one another was simulated by allowing little connectivity between the two simulated hemispheres, and one different output for each hemisphere. Finally, a *cooperative model* was also simulated, by specifying strong connectivity between hemispheres and one single output layer shared by the two hemispheres. Compared to the *callosal relay* model - in which information targeting the RH is simply transferred to the LH -, the other two models both represent different interpretations of the broad *direct access* framework described above. They differ in the fact that the *cooperative* model allows for hemispheric cooperation, while the *callosal relay* model specified in the study doesn’t. Crucially, what Weems & Reggia observed was that the *cooperative direct access* framework provided the closest resemblance with human data.

However, it is worth noting that in both the SERIOL (2001; 2005) and the connectionist framework by Weems & Reggia (2004) the architecture of each model is largely theory-driven. If on the one hand this allows the computational simulations to be embedded in a broader theoretical framework, on the other hand this makes it difficult to tell what the "computational core" of the visual field effect truly is, and whether the whole hypothesized architecture of the model is necessary to account for the visual field effect. In addition, in both computational frameworks a relatively limited training set was used (3650 words for the SERIOL and only 60 words in the study by Weems & Reggia).

1.4 Aims of the study

The present study aims at exploring the nature of the visual field effect in lateralized reading. In particular, the aim of Experiment 1 is to explore the effect of different psycholinguistic variables on the visual field effect in lateralized reading. This is done under the assumption that greater sensitivity towards word length and orthographic neighborhood in the LVF/RH than in the RVF/LH complies with a *callosal relay* model and a *single orthographic lexicon*, while different sensitivity towards word frequency and imageability between the two hemispheres, without a concurrent visual field-by-length or neighborhood interaction effect, rather complies with the hypothesis implying a *direct access* and *two orthographic lexicons*. While assuming that a mixture of *direct access* and *callosal relay* phenomena gives rise to the visual field effect, in Experiment 1 we will quantify the relative contribution of either mechanism towards this empirical phenomenon.

At the same time, Experiment 1 explores the extent to which the effects of psycholinguistic variables on the visual field effect are stable across groups of subjects characterized by a different pattern of functional hemispheric organization. In this regard, a sample of left-handers and a sample of right-handers were enrolled, under the assumption that left-handers show a more heterogeneous pattern of hemispheric dominance than right-handers.

In Experiment 2, we will leverage a simple and theory-free computational approach based on Naïve Discriminative Learning (Baayen et al., 2011) to explore the possible core mechanism underlying the visual field effect, conceptualized as the simplest computational operation necessary for the visual field effect (and its interactions with psycholinguistic factors) to arise. To do so, we will leverage an extensive training set derived from a linguistic corpus.

2. Experiment 1

2.1 Materials and Methods

2.1.1 Participants

One hundred and twenty neurologically healthy volunteers with normal or corrected-to-normal vision participated in the first experiment. All participants were Italian university students. One half of the participants (N= 60, 50% female, mean age= 23.07, sd= 2.79, mean education= 14.70, sd= 2.07) was right-handed. The other half (N= 60, 50% female, mean age= 22.03, sd= 3.27, mean education= 14.28, sd= 1.75) was left-handed[3]. The group of right-handers had a *mean* right-handedness of 89.72, *sd*= 13.05, while the group of left-handers had a *mean* handedness= -50, *sd*= 28.12, which was measured according to a laterality index computed on the Edinburgh Handedness Inventory (Oldfield, 1971): [(Right-Left)/(Right+Left)]*100.

2.1.2 Stimuli

There were 160 words and 160 pronounceable pseudowords, all shown in upper case. Regular (phonologically and orthographically plausible) pseudowords were preferred over implausible non-words (e.g. strings of consonants) to assure that lexical decision was based on lexical access rather than on phonotactic (and graphotactic) regularity. Indeed, in a lexical decision task in which non-words are implausible, participants can simply use orthographic plausibility (rather than actual lexical access) as a strategy to respond, i.e., to distinguish words from non-words. This is testified by evidence suggesting that patients with Pure Alexia have little or no difficulty in rejecting implausible non-words in a lexical decision task (Ablinger & Domahs, 2009; Cohen & Dehaene, 2000). In an experimental setup in which lexical access is not necessary to resolve the task, testing the hypothesis of different lexicons in the two cerebral hemispheres would become rather challenging. Words (Supplementary Table S1) were 80 4-letter and 80 5-letter disyllabic nouns taken from the "*Corpus e lessico di frequenza dell'italiano scritto*" (CoLFIS) database

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[3] Recruitment was carried out through the Bicocca SONA system, the university online experiment management platform. Such system permits targeted recruitment of left-/right-handed male/female participants. This allowed us to obtain a sample perfectly matched for sex and manual preference.

(Bertinetto et al., 2005), constituted by 3798275 words. The stimuli were selected to exclude noun-verb homographs, to avoid any lexical ambiguity. The structure of the 4-letter words was consonant-vowel-consonant-vowel (CVCV) and consonant-vowel-consonant-consonant-vowel (CVCCV) for the 5-letter words. For the 5-letter words, we excluded double consonants (e.g. BIRRA, beer; CASSA, box/pay desk) and the orthographic bigrams (or trigrams) GN, GL(+I), SC(+I/E), which in Italian correspond to the single phonemes /ɲ/, /ʎ/ and /ʃ/, respectively. For both word length conditions (4 and 5 letters)[4], 40 stimuli were high-frequency words (absolute frequency above 100), while 40 were low-frequency words (absolute frequency below 50). These frequency ranges were chosen in order to assure comparability between the present data and those from Bonandrini et al., 2020.

The appropriateness of our choice of high- and low-frequency stimuli was also cross-checked via the frequency norms from SUBTLEX-IT (Crepaldi et al., 2013). In line with Brysbaert et al. (2018), low frequency words have been typically defined as associated with <5 frequency per million and high-frequency words as having a frequency greater than 100 occurrences per million words. The average frequency per million words of our stimuli was 3.112 for low-frequency words (95% Confidence Interval= 2.215 – 4.008) and 240.076 for high-frequency words (95% Confidence Interval= 87.394 – 392.758). High-frequency words had also significantly higher log frequency-per-million values (mean= 4.35, median= 4.24, sd= 1.33) than low-frequency words (mean= 0.56, median= 0.69, sd= 1.21, U= 33, $p< 0.001$), as well as higher Zipf values (van Heuven et al., 2014) (mean= 4.89, median= 4.84, sd= 0.58)[5] than low-frequency words (mean= 3.17, median= 3.29, sd= 0.72, U= 33, $p < 0.001$).

In addition, stimuli were given imageability values according to the mean ratings on a 7-points Likert scale[6] of 21 previously recruited volunteers. The 160 pseudoword stimuli[7] (Supplementary Table S2) were randomly generated using the same CV structure of 4-letter (CVCV) and 5-letter

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[4] We adopted the contrast between 4 and 5 letters in order to use only two-syllable stimuli. Adopting longer strings would have implied potentially using stimuli with a different number of syllables, that would have resulted in greater phonological and visuo-spatial load, potentially modulating hemispheric differences in stimuli processing.

[5] Frequency per million and Zipf values were estimated after cleaning the raw corpus for items with a frequency equal to 1 and entries with no alphabetic characters.

[6] The question adopted for imageability rating was: "How easily can you visualize in your mind a vivid image associated to each of these words?"

[7] During manuscript revision, we noticed that two pseudowords are actual, although extremely infrequent, lexical strings (CEBO [a type of primate], MUGO [a type of pine tree]). For this reason, they were excluded from analyses. As a result, the final database included 158 pseudoword stimuli.

(CVCCV) word stimuli and individually checked in order to avoid illegal items. For the 5-letter pseudowords the same consonant clusters included in the 5-letter words were employed.

The Orthographic Levenshtein Distance 20 measure (OLD20) (Yarkoni et al., 2008), that indicates the average amount of insertions, deletions, and substitutions required to transform a target letter string into each of its 20 most similar words, was chosen as a measure of orthographic neighborhood. The OLD20 values for the 160 word stimuli were taken from the PhonItalia corpus (Goslin et al., 2014), which is based on the same corpus we adopted for stimuli selection (CoLFIS).

2.1.3 Task and procedure

Each subject was presented with a lateralized lexical decision task programmed in E-Prime (version 2.0, Psychology Software Tools Inc.) and administered by means of a Lenovo ThinkCentre PC. In particular, during each trial, participants were first presented with a central fixation cross, after which a word or a pseudoword occupying about 5.72° (on average) horizontally and 1.23° vertically, briefly appeared unilaterally either left or right from the center of the screen. Contrary to Hausmann et al. (2019), who presented two lateralized stimuli in each trial to implicitly control for eye movements, we presented just one stimulus at a time, and we explicitly controlled for eye movements. Recent research suggests that unilateral presentation should be preferred to bilateral presentations in order to be able to elicit sizeable orthographic neighborhood effects (Mills et al., 2022). Subjects were asked to indicate with a mouse key press whether the previous stimulus had been either a word or a “non-word”. After each trial, a slide depicting grayscale random dots appeared for 1 second to minimize inter-trial visual after-effects. According to the proposal put forward by Bourne (2006), we employed an eye tracking device (EyeLink 1000 – SR Research, sampling rate = 1000 Hz) to control for eye movements. In particular, we adopted a procedure similar to that employed by Tomkins (2020): during each trial, eye movements were monitored while the central fixation cross was presented. As soon as each subjects’ dwell time in a squared window of 1° around the central position reached the threshold of 250 ms, a stimulus (either word or pseudoword) appeared left or right from the fixation cross. Stimuli appeared for 128 ms with an eccentricity of 3.5° between the internal boundary of each stimulus and central fixation. This eccentricity parameter was chosen according to the conservative threshold suggested by Bourne (2006). If during a given trial the fixation time of the central cross did not reach the threshold of 250 ms in a time window of 10 s, that trial was considered as invalid.

In one half of the trials participants responded with their right hand, while in the other half they responded with their left hand (the order of such blocks was counterbalanced across subjects). Subjects were positioned in order to have their index and middle fingers on the left and right mouse keys. For each subject, independently from the responding hand, each of the two fingers was associated to either response (e.g., index finger = “WORD”, middle finger “NON-WORD”, or vice versa). The association between fingers and response was kept constant for each participant regardless of the responding hand, and it was counterbalanced across participants. Such double counterbalancing (responding hand and finger-target association) was done to minimize any possible effect of stimulus-response association.

After providing written informed consent, participants were instructed on the experimental procedure. The participants then comfortably sat in front of a computer screen (27”), with their chin placed on a chin rest, which was positioned to keep a distance of 70 cm between screen and participants’ eyes. The experimenter then positioned the eye tracker (desktop mount) in order to find the best configuration from which each participant’s dominant eye (as indicated in the Oldfield inventory) could be tracked. In one right-handed subject the left eye was tracked instead of the dominant right one, due to poor calibration with this latter. The right eye was tracked in 48/60 right-handed volunteers and in 18/60 left-handed volunteers. Then, participants underwent a brief training session during which two blocks of trials were presented. Before each trial block, the experimenter told the participants with which hand they had to respond and calibrated the eye tracking system according to a 5-point calibration procedure. For the training session, we employed 32 stimuli (16 words and 16 pseudowords) different from those used during the proper experimental session. During the training blocks (but not during the experimental phase) participants received feedback on their performance. After the training session, two experimental blocks (160 stimuli each) were administered. For each participant, the order of the responding hand and the finger-response association was kept fixed among training and experimental trials. As for the training session, also during the experimental session two calibration procedures (one before each experimental block) were run. Such procedures allowed us to reach an average tracking precision of 0.209° (sd = 0.066). The order of presentation of the stimuli was completely randomized within each subject. Each participant saw each stimulus only once to avoid any learning effect, possibly capable of smoothing hemispheric differences in behavioral performance.

The study was run according to the guidelines of the declaration of Helsinki (World Medical Association, 2001) and was approved by the ethical committee of the Università degli Studi di Milano-Bicocca (Commissione per la Valutazione della Ricerca, approval code: RM-2018-127).

2.1.4 Data analysis

Data points from right-handed (19200 records) and left-handed (19200 records) samples were merged in one single dataset. First, we discarded trials in which no response had been recorded (159 in right-handers and 110 in left-handers) and those in which response had been faster than or equal to 250ms (190 trials in right-handers and 126 trials in left-handers). Trials in which no stable fixation had been recorded were also discarded (748 in right-handers and 1026 in left-handers). The final dataset included 36041 records, 18103 for right-handers and 17938 for left-handers.

For each subject, separately for each trial, accuracy of responses in dichotomous form (1 = correct, 0 = incorrect) and log-transformed RTs of accurate responses (i.e. RTs of errors were discarded) were employed as dependent variables in a series of Mixed-effects models. Subjects and stimuli were modeled as random intercepts (Baayen, 2008; Mills et al., 2022)[8]. Logarithmic transformation (Baayen, 2008) was adopted to obtain a better approximation to a Normal distribution than that of raw RTs (see Supplementary Figure S1). Accuracy data were analyzed by means of logistic regressions. All analyses were performed by means of the statistical software R (4.0.3) and the lme4 package (Bates et al., 2015). Dummy coding of dichotomous variables was carried out, resulting in the weights 1 and -1 being attributed to factor levels in alphanumeric order (e.g., factor “Length”, level “4 letters” = 1, level “5 letters”= -1; factor “Visual Field”, level “LVF”= 1, level “RVF”= -1).

When necessary, for both accuracy and RTs data, χ^2 post-hoc pairwise comparisons were performed on significant interaction effects by means of the *testInteraction* function of the package Phia (De Rosario-Martinez, 2013) and corrected according to the Bonferroni method. This was done in order to keep Type I error under control in the most conservative possible way.

Preliminary analyses revealed the visual field variable to modulate performance only for words (and not for pseudowords), and that the hand with which participants responded does not interact with the effect of visual field on performance (See Supplementary Materials for further details).

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[8] Modelling with maximal random structures was attempted, but none of the maximal models reached convergence.

Analyses on the variables of interest were conducted on word stimuli only, to quantify the extent to which word length (4 vs. 5 letters), orthographic neighborhood [i.e., OLD20 (scaled)], word frequency (high vs. low), and imageability (scaled) interact with the visual field factor, and to explore whether group (left-handers vs. right-handers) further modulates these interaction effects. For all variables, simple effects were also included in the model[9].

2.2. Results

Performance was significantly better than chance level in both the LVF/RH (mean accuracy= 0.627, sd = 0.142, V = 6369, p< 0.001) and RVF/LH (mean accuracy= 0.728, sd= 0.131, V = 7023, p< 0.001).

For what concerns accuracy data (see Supplementary Table S5), a significant main effect of visual field was detected ($\chi^2(1)= 245.178$, $p< 0.001$), indicating greater accuracy associated with words projected to the RVF/LH (mean= 0.728, sd= 0.131) than for words projected to the LVF/RH (mean= 0.627, sd= 0.142). The effect of frequency was also significant ($\chi^2(1)= 28.132$, $p< 0.001$, Figure 1a), indicating better performance for high-frequency words (mean= 0.728, sd= 0.127) than low-frequency words (mean= 0.627, sd= 0.124), together with the effect of word length ($\chi^2(1)= 40.714$, $p< 0.001$, Figure 1b), indicating greater accuracy for 4-letter (mean= 0.740, sd= 0.120) words than 5-letter words (mean= 0.616, sd= 0.139). The two-way interaction between visual field and OLD20 was significant ($\chi^2(1)= 12.632$, $p< 0.001$). The nature of this interaction was further explored in a separate analysis, that revealed a greater effect of orthographic neighborhood in the RVF/LH than in the LVF/RH ($\chi^2(1)=10.487$, p= 0.001, Figure 1c). A significant group-by-visual field interaction effect was present ($\chi^2(1)= 23.713$, $p< 0.001$, Figure 1d), indicating better accuracy for left-handers (mean= 0.659, sd= 0.137) than right-handers (mean= 0.595, sd= 0.141) for word stimuli projected to the LVF/RH ($\chi^2(1)= 7.906$, $p = 0.030$), with no such group difference for stimuli projected to the RVF/LH ($\chi^2(1)= 0.001$, $p = 1.000$). All other effects were not significant (p values > 0.125).

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[9] It is worthy to note that the goal of Experiment 1 is to explore the relative contribution of word frequency, imageability, length and orthographic neighborhood in modulating the visual field effect, by comparing the magnitude of the interaction effects of word frequency, imageability, length and OLD20 with visual field. Since the exploration of three-way interactions between psycholinguistic variables would be of little help in answering our experimental question, they were not included in the statistical models we adopted.

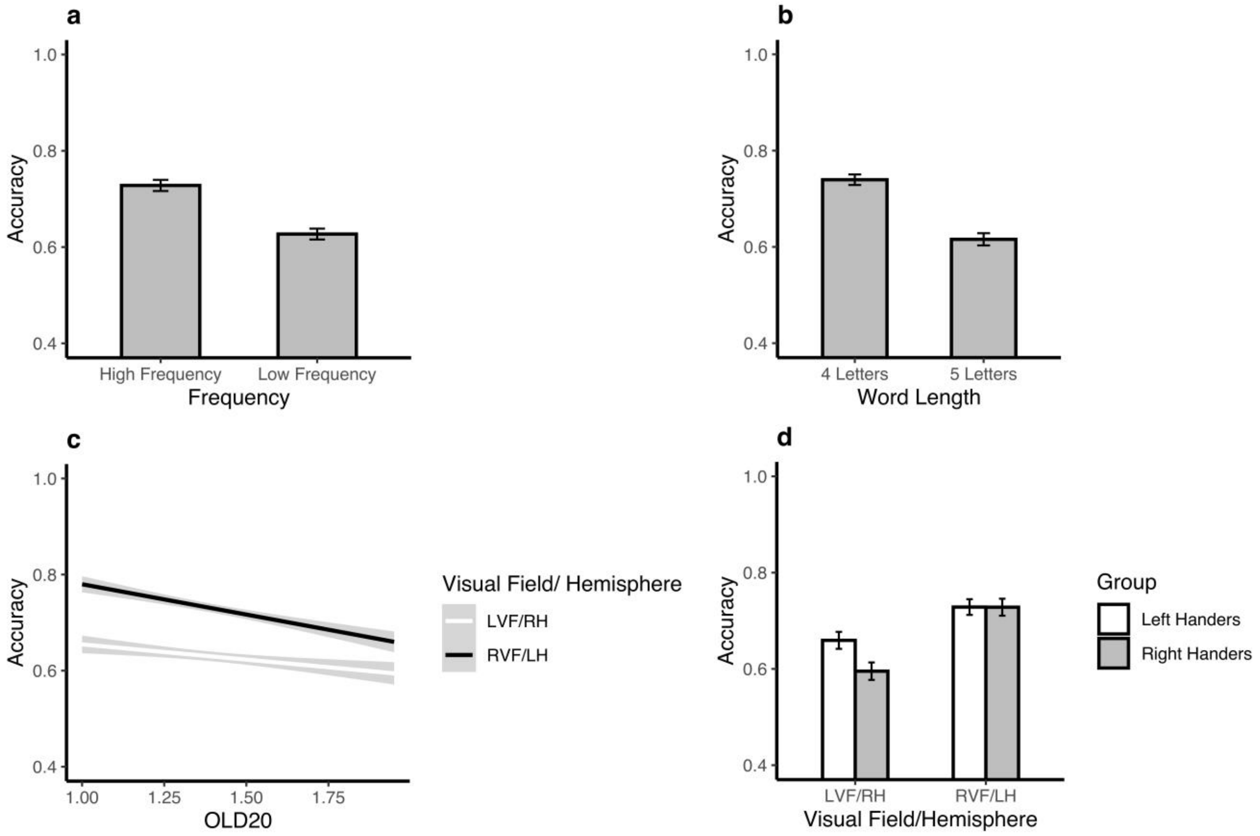

Figure 1: Results of analyses on accuracy data (proportion of accurate responses): (a) main effect of word frequency; (b) main effect of word length; (c) orthographic neighborhood (OLD20)-by-visual field interaction; (d) group-by-visual field interaction.

Analyses on RTs revealed the significant main effect of the variables visual field (*F*(1, 12027.018)= 106.388, *p*< 0.001), indicating faster RTs for words projected to the RVF/LH (mean= 750.206, sd= 168.883) than to the LVF/RH (mean= 786.075, sd= 188.997), group (*F*(1, 117.033)= 4.723, *p*= 0.032), indicating faster responses for left-handers (mean= 729.563, sd= 145.001) than right-handers (mean= 799.809, sd= 193.809), frequency (*F*(1,153.501)= 54.955, *p*< 0.001; Figure 2a), indicating faster responses for high-frequency words (mean= 734.221, sd= 171.326) than low-frequency words, (mean= 800.204, sd= 182.955), length (*F*(1, 151.856)= 39.964, *p*< 0.001; Figure 2b), indicating faster RTs for 4-letter words (mean= 741.069, sd= 171.750) than 5-letter words (mean= 793.535, sd= 182.583), and OLD20 (*F*(1, 151.847)= 8.458, *p*= 0.004; Figure 2c). The effect of imageability showed a trend towards significance (*F*(1, 152.234)= 3.839, *p*= 0.052; Figure 2d). Also for RTs a significant group-by-visual field interaction effect was detected (*F*(1, 12012.525)= 6.416, *p*= 0.011, Figure 2e), indicating that while there are no group differences for stimuli presented to the RVF/LH ($\chi^2(1)$= 3.062, *p*= 0.481), left-handers (mean= 742.989, sd= 156.512) are faster than right-handers (mean= 829.160, sd= 209.222) in the LVF/RH ($\chi^2(1)= 6.220$, $p_{\text{uncorrected}}= 0.013$), although this effect does not survive correction for multiple comparisons ($p_{\text{Bonferroni-corrected}}= 0.076$).

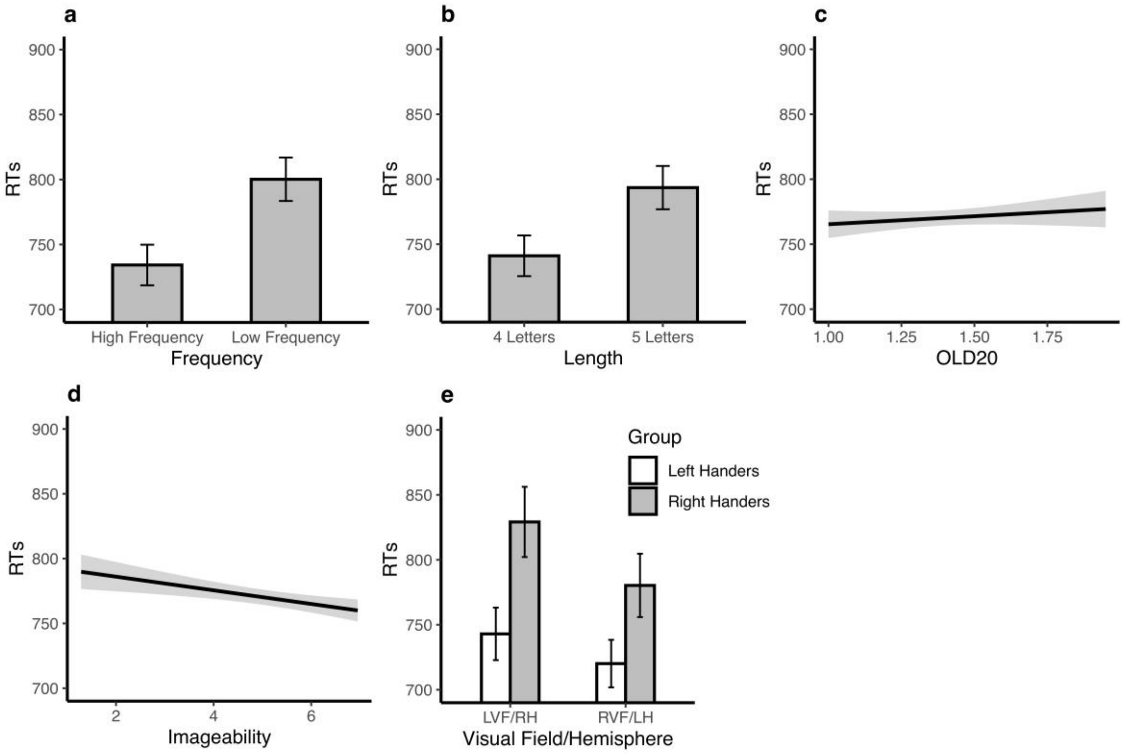

Figure 2: Results of analyses on RTs: (a) main effect of word frequency; (b) main effect of word length; (c) effect of orthographic neighborhood (OLD20); (d) effect of imageability; (e) group-by-visual field interaction.

Crucially, a visual field-by-frequency interaction was observed ($F(1, 12020.852)= 4.448$, $p= 0.035$, Figure 3). In order to explore the meaning of this interaction, post-hoc analyses pairwise tests were initially conducted, but they provided little information on the direction of the interaction effect, as they all turned out to be significant (all p values < 0.001), apart from the comparison between high-frequency words in the LVF/RH and low-frequency words in the RVF/LH, whose significance did not survive correction for multiple comparisons: $p_{\text{uncorrected}}= 0.024$, $p_{\text{Bonferroni-corrected}}= 0.145$). Therefore, in order to further explore the meaning of this interaction effect, we computed (for each subject) the difference between RTs for low-frequency and high-frequency items in each visual field/hemisphere. The frequency effect turned out to be larger in the RVF/LH (mean= 78.744, sd= 77.947) than in the LVF/RH (mean= 50.453, sd= 107.638, V = 4354, p = 0.018).

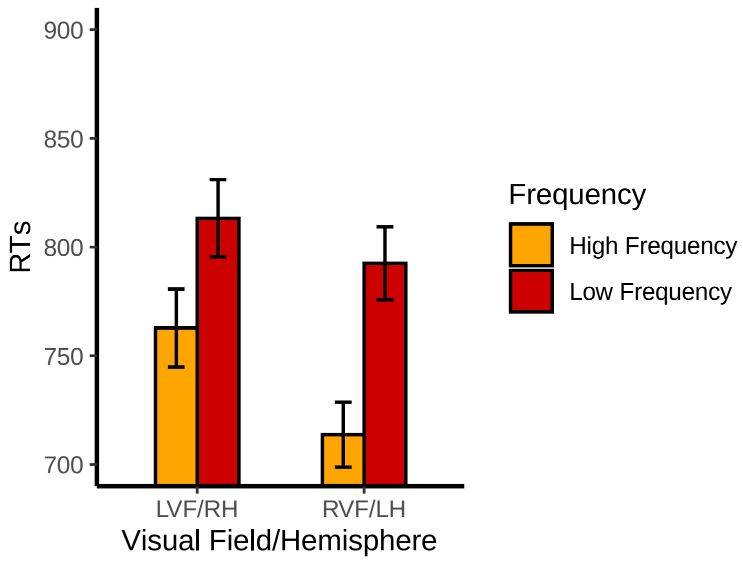

Figure 3: Visual field-by-frequency interaction for RTs (ms). Error bars indicate mean standard errors. All pairwise post-hoc comparisons turned out to be significant ($p_{\text{Bonferroni-corrected}} < 0.001$), with the only exception of the comparison between high-frequency words in the LVF/RH and low-frequency words in the RVF/LH, whose significance did not survive correction for multiple comparisons: $p_{\text{uncorrected}} = 0.024$, $p_{\text{Bonferroni-corrected}} = 0.145$.

2.3. Interim Discussion

Left and right-handed subjects, who are typically associated with weak and strong left functional hemispheric dominance for language, respectively (Pujol et al., 1999), were administered with a lateralized lexical decision task in which word length, orthographic neighborhood (i.e., OLD20), word frequency and imageability were modulated. According to the *callosal relay-single orthographic lexicon* framework, word length and orthographic neighborhood were expected to have a greater impact on performance for stimuli projected to the LVF/RH than to the RVF/LH. Conversely, according to the *direct access-two orthographic lexicons* framework, interaction effects between visual field and word frequency and/or imageability were anticipated. Although recent evidence suggests that *direct access* and *callosal relay* phenomena are likely to co-exist at the neural level (Chu & Metlzer, 2019) the relative contribution of these mechanisms towards the visual field effect and its interactions with psycholinguistic variables is unknown.

Analyses on RTs revealed a significant visual field-by-frequency interaction, indicating that the magnitude of the word frequency effect is smaller for stimuli projected in the LVF/RH than in the

RVF/LH. This result appears to be in line with the predictions of the *direct access-two orthographic lexicons* framework. Conversely, no evidence of stronger effects of word length or orthographic neighborhood for stimuli projected in the LVF/RH than in the RVF/LH (as the *callosal relay-single orthographic lexicon* framework would have anticipated) were detected. Analyses on accuracy did highlight an interaction effect between visual field and orthographic neighborhood (OLD20), but the direction of this effect is the opposite of that anticipated from the *callosal relay-single orthographic lexicon* framework: the effect of OLD20 for accuracy was comparatively greater for stimuli projected in the RVF/LH than in the LVF/RH. The orthographic neighborhood effect has been interpreted as due to top-down influence from prior orthographic knowledge to letter-level processing (Andrews, 1992; Coltheart & Rastle, 1994). In line with this view, a greater orthographic neighborhood effect for stimuli projected in the RVF/LH than in the LVF/RH suggests that the interaction effect between visual field/hemisphere and orthographic neighborhood is best explained by stronger lexical-to-letter-level top-down facilitation in the LH than in the RH due to stronger lexical orthographic representations in the LH than in the RH, rather than by more costly extraction of abstract letter identities in the RH than in the LH -as the *callosal relay-single orthographic lexicon* framework described by Ellis (2004) would have anticipated. A possible alternative interpretation based on a connectionist framework (see for instance Plaut et al., 1996) could define the orthographic neighborhood effect as due to attractor dynamics (i.e., the ways in which specific patterns of activation of the units can be recognized by the system in order to produce an output) within distributed lexical representations. Yet, the different effect of orthographic neighborhood in the two visual field/hemispheres (i.e., the visual field-by-OLD20 interaction) suggests that such dynamics (and therefore the lexical representations) are different between visual fields/hemispheres, in line with the *direct access-two orthographic lexicons* framework.

It is also worthy to note that although an overall trend towards a significant effect of imageability emerged for RTs, no significant interaction with visual field/hemisphere emerged. This result is apparently at odds with previous neuropsychological evidence (e.g., Bonandrini et al., 2020; Saffran & Coslett, 1998). However, it is possible that the lack of a facilitating effect of imageability (which is a semantic factor) for words presented in the RH in healthy participants could be due to lower reliance - compared to patients with a damaged LH visual word form system - on semantic cues while engaging in a lexical decision task.

As far as the relationship between functional brain lateralization, psycholinguistic variables, and the visual field effect is concerned, Experiment 1 revealed a group-by-visual field interaction suggesting better performance for left-handers than right-handers for stimuli projected to the LVF/RH[10] and not for stimuli projected to the RVF/RH. The observation of a significant performance advantage in left-handers limited to LVF/RH stimuli can be interpreted in light of previous evidence suggesting that left-handers are associated with a comparatively smaller functional lateralization of the (spoken) language system than right-handers (Pujol et al., 1999), and that the functional lateralization of orthographic processing co-varies with that of spoken language (Cai et al., 2010). The overall lower functional lateralization of the language system in left-handers would explain why the cost of projecting stimuli to the LVF/RH (relative to the RVF/LH) is smaller than in right-handers.

Noteworthy, the interaction between visual field and group did not further interact with any psycholinguistic variable, suggesting that the psycholinguistic neurocognitive processes giving rise to the visual field effect are not affected by the overall functional brain lateralization pattern. These results also suggest that the psycholinguistic processes giving rise to the visual field effect do not vary between different functional lateralization groups on a quantitative level (i.e., psycholinguistic variables interact with the visual field effect in a similar way in left- and right-handers). Rather, the same mechanisms seem to underly the visual field effect in left- and right-handers, although with quantitative differences in their expression between different functional lateralization groups. In other words, this implies that whichever mechanism is responsible for poor performance in the LVF/RH in right-handed participants, its effect is less pronounced in left-handers, resulting in a comparatively better performance in the LVF/RH than in right-handers.

More broadly, Experiment 1 highlights a lexical locus for the emergence of the visual field effect. Although a mixture of *direct access* and *callosal relay* phenomena has been described at the neural level (Chu & Meltzer, 2019), the present evidence highlights the more prominent role of the *direct access* mechanisms anticipated by the two orthographic lexicons framework in giving rise to the visual field effect. In particular, the interaction between visual field and frequency in Experiment 1 suggests that the visual field effect could be due to differences in how lexical orthographic knowledge is stored and/or accessed in the two hemispheres. This evidence suggests an association between the specialization of the left visual word form area (see for instance Cohen et al., 2000; Cohen et al., 2002; McCandliss et al., 2003; Dehaene & Cohen, 2011; Bouhali et al.,

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[10] This effect barely missed formal significance for RTs after correction for multiple comparisons.

2014) - or visual word form system, in a broader sense - for orthographic processing and the organization of lexical orthographic knowledge in the brain.

However, while this evidence aligns with previous data suggesting weaker/poorer organization of the orthographic processing system in the RH than in the LH (Bonandrini et al., 2020; Coltheart, 1980, 2000; Coslett & Saffran, 1989; Coslett & Saffran, 1994; Saffran et al., 1980; Saffran & Coslett, 1998), the available literature provides no suggestions on the possible mechanisms underlying such differences (i.e., interactions) in how lexical orthographic knowledge is stored and/or accessed in the two hemispheres. This topic will be specifically addressed in Experiment 2 by means of a computational modelling study.

3. Experiment 2

A crucial feature of the *direct access-two orthographic lexicons* account is the assumption that orthographic knowledge is stored and/or accessed differently in the two hemispheres. Results of Experiment 1 (and - in particular - the comparatively smaller word frequency effect for stimuli projected in the LVF/RH than in the RVF/LH) suggest that the RH orthographic lexicon being weaker/poorer than the LH one (Bonandrini et al., 2020; Coltheart, 1980, 2000; Coslett & Saffran, 1989; Coslett & Saffran, 1994; Saffran et al., 1980; Saffran & Coslett, 1998) could depend on the RH being less able than the LH to activate - on the basis of sub-lexical orthographic cues - specific lexical/semantic nodes.

According to the *Naïve Discriminative Learning* model (Baayen et al., 2011; Milin et al., 2017), the possibility for a given word representation to be effectively activated by a pre-lexical cue (e.g., a letter or group of letters) depends not only on how often this cue and this outcome co-occur, but also on how exclusive the cue-outcome relationship is (Baayen et al., 2011; Milin et al., 2017). Differently from other computational models of reading such as the interactive activation model (McClelland & Rumelhart, 1981), the dual route model (Coltheart et al., 2001) and the bilingual interactive activation model (Van Heuven, Dijkstra, and Grainger; 1998) that code frequency into the resting activation levels of word units, in the Naïve Discriminative Learning model the effect of frequency is not explicitly defined in the model, but rather emerges as a by-product of discriminative learning (see Baayen, 2010 for a discussion on this issue). Practically speaking, this means that multiple experiences with a given cue-outcome pair do not directly translate in greater activations of the corresponding output node (i.e., a frequency effect). Rather, this ultimately depends on the distinctiveness of the relationship between cues and outcomes. In this framework, the smaller frequency effect in the RH might be due to a breakdown in the association between cues and outcomes, resulting in poor informativity of orthographic cues towards the activation of specific lexical/semantic nodes.

In Experiment 2, we employed the *Naïve Discriminative Learning* model (Baayen et al., 2011; Milin et al., 2017) to simulate the result of learning of lexical orthographic knowledge in the two cerebral hemispheres. This computational approach was developed to simulate word processing via a two-layer symbolic network in which the input level is populated by letter n-grams as *cues*, and the output level is populated by whole words representing lexical/semantic units (defined as *lexomes*) as *outcomes*. Lexomes are defined as “pointers”, typically activated by orthographic cues, that in turn reference a location in a conceptual space (Milin et al., 2017; Sering et al., 2017; Milin, Divjak & Baayen, 2017). Critically, although lexomes do not have a one-to-one relationship with orthographic words, “in practice, they are associated with and computationally implemented as identifiers in the form of orthographic words” (Milin, Divjak & Baayen, 2017). The *Naïve Discriminative Learning* approach successfully simulated patterns of human responses in lexical decision tasks, such as the word frequency effect (e.g., Baayen et al., 2011). The critical feature of the model is that associations between input and output units develop through discriminative learning. Therefore, learning (and hence subsequent lexical access) is effective when there is a consistent and distinctive relationship between an orthographic cue and an outcome. This feature of the *Naïve Discriminative Learning* model makes it particularly apt at simulating learning of orthographic knowledge in the two cerebral hemispheres. Indeed, the observation of a smaller frequency effect in the LVF/RH vis-à-vis the RVF/LH suggests that the RH is less able than the LH to leverage sub-lexical orthographic cues to distinctively activate the specific corresponding lexical/semantic nodes. In other words, in the RH the association weights between pre-lexical cues and orthographic representations could be more similar to each other than in the LH, thus reducing the processing gain for high-frequency words over low-frequency words.

In Experiment 2, *Naïve Discriminative Learning* was used to simulate orthographic access. Notably, differently from the SERIOL model (Whitney, 2001; Whitney, 2008; Whitney & Lavidor, 2005) and the connectionist approach proposed by Weems and Reggia (2004), no structural architecture was imposed *a priori* to the model. These simulations were run with the ultimate aim of replicating the main effects of visual field and frequency, as well as to simulate the smaller frequency effect in the LVF/RH than in the RVF/LH described in Experiment 1.

3.1 Materials and Methods

3.1.1 Naïve Discriminative Learning

In basic terms, the *Naïve Discriminative Learning* approach conceives reading as a predictive process, through which readers activate the lexical/semantic node (or *lexome*) corresponding to a known word based on the available *cues* (letters and cluster of letters). It follows that each word is regarded as an *outcome* and its constituting n-grams (e.g., letters, bigrams, trigrams) as its *cues*.

During a *training* phase, the model estimates, for a given set of words, the intensity of the association (association weights) between each cue present in the word set and each possible outcome. This is accomplished via the estimation of the stable state (Danks, 2003) of a Rescorla-Wagner learning process (Rescorla & Wagner, 1972), whereby correct prediction of an outcome given the available cues leads to strengthening of cue-outcome associations weights, and misprediction results in weakened weights (Baayen et al., 2011; Milin et al., 2017). During the *test* phase, for each word contained in the test set, the probability of its identification is estimated by dividing its activation by the sum of the activations of its most activated competitors. Baayen and colleagues (2011) set the number of possible competitors to 20 to mirror orthographic neighborhood effects (Yarkoni et al., 2008), and eventually simulated reading times by log-transforming the inverse of the identification probability for each word in the test set.

In the original formulation of the *Naïve Discriminative Learning* model, input units were letter unigrams and bigrams, and output units were *lexomes* (Baayen et al., 2011; Milin et al., 2017). In this experiment, the same two-layer symbolic network was adopted to simulate the association between sub-lexical orthographic cues (letters and bigrams) and lexical-orthographic output nodes acting as *proxies* of word representations in the two cerebral hemispheres. In particular, learning was assumed to be efficient in the LH and inefficient in the RH, in line with previous literature suggesting little effects of learning proficiency on the activation of the right homologue of the visual word form system (Dehaene et al., 2015) and with previous computational work that modelled the RH as characterized by less efficient learning than the LH (Weems and Reggia, 2004). In the context of this experiment, the outcome of inefficient learning in the RH was achieved by introducing noise[11] in the association weights between cues and outcomes. By doing this, we

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[11] In this context, noise is conceptualized as a computational device adopted to artificially disrupt the distinctiveness of cue-outcome association weights, and not as a physical or biological entity. For possible biological interpretations of this mechanism, please refer to the General Discussion.

disrupted the discriminability of cue-outcome associations in the RH, while maintaining the sets of cues and outcomes identical between the two hemispheres[12].

To summarize, the phenomenon of interest is the visual field effect, accompanied by the comparatively smaller word frequency effect for stimuli projected in the LVF/RH than in the RVF/LH (as emerged from Experiment 1); the putative explanation of the phenomenon is that the RH is less able than the LH to activate - on the basis of sub-lexical orthographic cues - specific lexical/semantic nodes; the assumption of this explanation is that the outcome of the learning process must be less efficient in the RH than in the LH (otherwise the result would be a processing advantage for the RH over the LH); the computational implementation of this explanation is the simulation of the process of learning the associations between sub-lexical cues and lexical/semantic outcomes via the *Naïve Discriminative Learning* model with noise being introduced in the association weights between cues and outcomes in the RH to simulate less efficient learning in the RH than in the LH.

3.1.2 Model training

Word stimuli were taken from the Phonitalia corpus, containing 120,000 word entries (Goslin et al., 2014). Double entries (25495 words) were eliminated, thus leaving a total of 94505 words. Word frequencies were derived from the subtlex-it corpus (Crepaldi et al., 2013). If multiple entries were present in subtlex-it for a given word in the training corpus, duplicated entries were dropped and frequencies were summed. Words with frequency smaller than 2 were discarded, thus leaving a total of 66409 training items.

For each word (outcome), its set of cues (single letters and bigrams) was derived. Therefore, for the outcome "*cane*" (dog), the set of cues was: c_a_n_e_#c_ca_an_ne_e# (the symbol # represents a blank space in a bigram). To train the two-layer (grapheme-to-word) network in the context of "noiseless" efficient learning in the LH, the *ndl* R package (Arppe et al., 2015) was used. The function to estimate cue-outcome weights requires a set of outcomes (in this case words), a set of corresponding cues (in this case letters and bigrams) and a vector of frequencies that defines the frequency of each outcome (in this case corresponding to word frequencies according

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[12] In comparison with the modulation of learning parameters, the addition of noise in the cue-outcome matrix provided a more efficient way to disrupt the discriminability of cue-outcome associations. For further details, see Supplementary Simulations in the Supplementary Materials.

to the subtlex-it corpus). The output of this function is a matrix of weights for cue-outcome pairs representing the equilibrium state of learning of the Rescorla-Wagner model (Danks, 2003).

3.1.3 Noise

The obtained cue-outcome weight matrix representing optimal learning was used to simulate reading in the LH. To characterize the coupling between orthographic cues and lexical/semantic nodes in the RH, random uniform noise was then introduced in such matrix. Given that there was no *a priori* indication in the literature on the amount of noise necessary to simulate RH reading, different simulations were run implementing varying degrees of noise. Also, since results of the simulations were non-deterministic, different permutations of each simulation were run.

In particular, each cue-outcome weight was multiplied by a number ranging from 0 to 1, acting as a "scaling factor". The closer this number to 1, the lower the noise and the attenuation of the cue-outcome weight. We adopted a scaling factor instead of adding or subtracting a random number to the weight to avoid that noise could produce (by chance) paradoxically bigger weights in absolute value (i.e., by adding a positive random number to a positive weight or adding a negative number to a negative weight) than the noiseless condition, or even change the sign of the weights. Noise range was treated as a free parameter, and 20 possible levels were considered. For each of them (see Table 2), a matrix with the same dimensions of that of the cue-outcome weights was produced, containing random scaling factors with a uniform distribution between a maximum and a minimum. The maximum was set to 1 in all simulations, to allow the possibility for some cue-outcome weights to be minimally affected by noise.

Table 2: Noise ranges for the simulation of learning in the RH orthographic lexicon.

Model	***1***	***2***	***3***	***4***	***5***	***6***	***7***	***8***	***9***	***10***
Range of scaling factors	0.96-1.00	0.91-1.00	0.86-1.00	0.81-1.00	0.76-1.00	0.71-1.00	0.66-1.00	0.61-1.00	0.56-1.00	0.51-1.00
Model	***11***	***12***	***13***	***14***	***15***	***16***	***17***	***18***	***19***	***20***
Range of scaling factors	0.46-1.00	0.41-1.00	0.36-1.00	0.31-1.00	0.26-1.00	0.21-1.00	0.16-1.00	0.11-1.00	0.06-1.00	0.01-1.00

Each weight in the cue-outcome weight matrix was multiplied by its corresponding scaling factor in the scaling factor matrix. For each noise range, the position of the scaling factors in the scaling factor matrix was permuted 120 times (to parallel the number of human participants in

Experiment 1). Hence, for each noise range, 120 noise-attenuated weights matrices were obtained (2400 simulations in total).

3.1.4 Testing

The word stimuli adopted in experiment 1 were used as targets. Lexical activation and simulated RTs were then computed as in Baayen et al. (2011). This was done for the noiseless model of the LH and for each of the 120(permutations)*20(noise ranges) models simulating the RH lexicon. For each noise range, results were averaged between different permutations. This procedure yielded, for each target, a vector of simulated RTs for LH reading and 20 vectors (one for each noise range) of simulated RTs for RH reading.

As a first sanity check, in order to evaluate the face-validity of the simulations, simulated RTs for the LH were correlated with real item-averaged log(RTs) from Experiment 1, for stimuli projected in the RVF/LH. For each of the 20 RH reading simulations, the effect of visual field/hemisphere was computed as the difference between their simulated RTs and the simulated RTs yielded by the "noiseless" (LH) model. For all simulations, the frequency effect was then computed as the difference between simulated RTs for low frequency vis-à-vis high-frequency items, with the aim of exploring the effect of noise on the frequency effect in the RH.

Subsequently, RTs of the models simulating reading in the RH were correlated with human data. The RTs of the simulation providing the strongest correlation with human data were then entered, together with simulated RTs obtained from "noiseless" learning in the LH, in a mixed ANOVA with Visual Field/Hemisphere as a within-items factor and Frequency as a between-items factor. The same ANOVA was run on human data (after log-transformation), with the aim of exploring the extent to which simulations were effective in recreating the effects observed for human data. P values from post-hoc pairwise comparisons were corrected according to the Bonferroni method. Comparisons between human data and simulations were run on word targets in which simulated data were available in the training set. These analyses were run on the Jamovi software (The jamovi project, 2021).

3.2 Results

Data from three low-frequency targets were not included in the model, due to the absence of these stimuli in the training set (DOGE [= doge], GARBO [= grace], GARZA [= gauze]). As far as the “noiseless” LH model is concerned, a significant positive correlation with human data for stimuli projected to the RVF/LH was observed (r= 0.475, p < 0.001). For what concerns simulation of RH reading, Figure 4 shows that, as noise increased, the magnitude of the effect of visual field/hemisphere increased and the magnitude of the frequency effect in the (simulated) RH decreased.

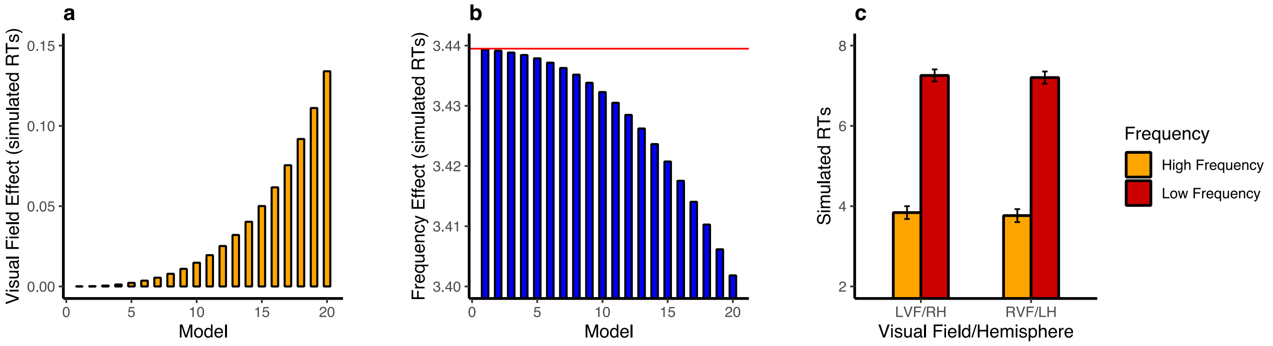

Figure 4: (a) Magnitude of the visual field/hemisphere effect for each “noisy” RH simulation. Model 1 is associated with the minimum amount of noise, while model 20 is associated with the maximum amount of noise. The visual field/hemisphere effect was computed as the difference between the average RTs from each “noisy” simulation and the average RTs yielded by the “noiseless” simulation. (b) Magnitude of the frequency effect for each “noisy” RH simulation. Model 1 is associated with the minimum amount of noise, while model 20 is associated with the maximum amount of noise. The frequency effect was computed as the difference between simulated RTs for low frequency and high-frequency items. The red line indicates the frequency effect for the “noiseless” LH simulation. (c) Visual field-by-frequency interaction for simulated RTs. Error bars indicate mean standard errors.

All models simulating RH-yielded RTs showed a significant (all *p* values < 0.001) positive correlation with human RTs. Model 20 (*r*= 0.32260) yielded the strongest correlation with human data (all other *r*s ≤ 0.32250).

Simulated RTs from model 20 were therefore used, together with simulated RTs from the “noiseless” model simulating LH reading, to draw a comparison with human data.

The mixed-effects ANOVA on human data yielded a significant main effects of visual field/hemisphere (*F*(1,155)= 39.516, *p*< 0.001, η^2_p= 0.203) and word frequency (*F*(1,155)= 34.120, *p*< 0.001, η^2_p= 0.180), together with a significant visual field/hemisphere-by-frequency interaction

(*F*(1,155)= 8.666, *p*= 0.004, η^2_p= 0.053). Pairwise comparisons revealed that RTs associated with low-frequency stimuli projected to the LVF/RH were significantly longer than those associated with high-frequency stimuli projected to the LVF/RH (*t*(155)=-3.852, *p*< 0.001) and those associated with low-frequency stimuli projected to the RVF/LH (*t*(76)=2.282 , *p*= 0.050). As anticipated by Experiment 1, the magnitude of the frequency effect for stimuli projected to the LVF/RH (log(RTs)=0.067) is smaller than that yielded by stimuli projected to the RVF/LH (log(RTs)=0.114).

The mixed-effects ANOVA on simulated data yielded a significant main effects of visual field/hemisphere (*F*(1,155)= 908.905, *p*< 0.001, η^2_p=0.854) and frequency (*F*(1,155)= 240.695, *p*< 0.001, η^2_p= 0.608), together with a significant visual field/hemisphere-by-frequency interaction (*F*(1,155)= 18.032, *p*< 0.001, η^2_p= 0.104). Post-hoc pairwise comparisons revealed that RTs associated with low-frequency stimuli projected to the LVF/RH were significantly longer than those associated with high-frequency stimuli projected to the LVF/RH (*t*(155)=-15.506, *p*< 0.001) and those associated with low-frequency stimuli projected to the RVF/LH (*t*(76)=20.140 , *p*< 0.001). As for human data -and as shown by Figure 4b-, the magnitude of the frequency effect for the RH simulation in model 20 (simulated RTs= 3.402) is smaller than that of the LH simulation (simulated RTs= 3.439). This evidence is also supported by the fact that, across the 120 permutations of model 20, the magnitude of the frequency effect was significantly smaller than that observed for the “noiseless” LH simulation (t(119)= -2.433, p = 0.017).

3.3 Interim Discussion

In Experiment 2, the stable state (Danks, 2003) of the learning process associating pre-lexical cues and orthographic nodes was simulated by means of *Naïve Discriminative Learning*. The same two-layer symbolic network adopted by Baayen et al. (2011) and Milin et al. (2017) was used to model the lexical orthographic representations in the two cerebral hemispheres. In particular, to simulate the RH, a variable amount of noise was introduced in the matrix containing the weights of the connections between the layer representing letters and bigrams and the layer containing the orthographic output nodes that we adopted as *proxies* of lexical representations (words). To simulate efficient orthographic learning in the LH, no noise was added in the cue-outcome matrix.

At a preliminary level, the progressive disruption of the distinctiveness of cue-outcome associations (i.e. by progressively adding noise) in RH simulations resulted in an increase of RTs, thus yielding a growth in the magnitude of the simulated visual field/hemisphere effect. Also, the progressive disruption of the distinctiveness of cue-outcome associations in RH simulations gave rise to a reduction of the magnitude of the simulated frequency effect in the RH. These qualitative data provide face validity to our methodology, by demonstrating that the poorer the discriminative learning process associating pre-lexical cues and lexical-orthographic outcomes, the longer the simulated RTs, and the smaller in magnitude the simulated frequency effect.

In addition, data from all simulations were positively correlated with human data (all p values < 0.001).

As far as RH simulations are concerned, the one providing the highest correlation with human data turned out to be the one with the greatest disruption of the distinctiveness of cue-outcome associations (scaling factors comprised between 0.01 and 1, thus providing the strongest attenuation of cue-outcome weights). Simulated RTs from this latter RH model, combined with those of the noiseless model simulating orthographic learning in the LH, reproduced the main effects of visual field/hemisphere (i.e. longer RTs for stimuli projected to the LVF/RH than to the RVF/LH) and frequency (i.e. longer RTs for low-frequency than for high-frequency words) described in human data, as well as, most importantly, the visual field-by-frequency interaction.

As Figure 4c indicates, the model produced a comparatively greater frequency effect than human data, and the effects of visual field and its interaction appear more subtle than those of human data. Such discrepancy could potentially be explained by the fact that (in line with Baayen et al., 2011), our simulations did not include mechanisms accounting for the general activation of the system to provide a time-out for responses (see for instance Grainger & Jacobs, 1996). However, as consideration of the effect sizes shows, for both human and simulated data the η^2_p is greatest for the visual field effect, followed by the frequency effect, in turn followed by the visual field-by-frequency interaction.

Taken together, these results suggest that the limited ability of the RH to leverage sub-lexical orthographic cues to distinctively activate the specific corresponding lexical/semantic nodes could represent a plausible mechanism underlying both the visual field effect and the compression of the frequency effect in the RH described for human data in Experiment 1. Of course, this is true provided that a considerable attenuation of the relationship between orthographic cues and orthographic output nodes is introduced in the RH. This finding emphasizes that the magnitude of hemispheric differences in the activation of lexical representations -as captured by the visual field effect in lateralized reading- is considerable.

It is worthy to note that in the present simulations noise was added at the end state of the learning process. This was done for practical reasons, because *Naïve Discriminative Learning* - as implemented in the ndl package (Arppe et al., 2015) - is meant to be parameter-free and it does not allow modifications in how learning is carried out. However, in our view, this doesn’t diminish the significance of the present results. Indeed, we were able to simulate the visual field effect and its interaction with psycholinguistic variables in the most compact approach to date (one parameter vs. the arguably more complex architectures adopted by Weems & Reggia and the SERIOL models). Also, these simulations identify in the less distinctive activation in the RH than in the LH of lexical/semantic nodes (given a set of orthographic cues) a possible “computational core” of the visual field effect, while leaving the door open for multiple interpretations of this effect: on the one hand, this could be the outcome of a poor learning process; on the other hand, this effect could mirror limited accessibility of such cue-outcome links after learning has occurred.

4. General discussion

4.1 On the nature of the visual field effect

In this study, we explored the nature of the visual field effect in lateralized reading. In this regard, two different functional brain models have been proposed for its interpretation. The *callosal relay – single orthographic lexicon* framework assumes that the RH is completely word blind, and the visual field effect represents the cost - for stimuli projected to the LVF and therefore first targeting the RH - to be perceived and transferred to the *single orthographic lexicon* located in the LH (Ellis, 2004; Ellis et al., 1988; Whitney, 2001). Accordingly, this framework predicts that word length and orthographic neighborhood should affect processing of information targeting the LVF/RH more than the RVF/LH. Hemispheric differences in the effects of word frequency or imageability are not excluded, but they should occur by virtue of greater costs in the RH in the processing steps occurring before lexical access. Therefore, potential interactions between visual field and word frequency or imageability should occur (according to the *callosal relay – single orthographic lexicon* framework) in conjunction with a greater effect of word length and orthographic neighborhood in the LVF/RH than in the RVF/LH. Conversely, the *direct access - two orthographic* *lexicons* framework suggests that the visual field effect represents asymmetries in hemispheric representation of orthographic knowledge (Coltheart, 1980, 2000; Coslett & Saffran, 1994; Luzzatti, 2003; Luzzatti et al., 1998; Saffran et al., 1980; Saffran & Coslett, 1998). This framework anticipates a different magnitude of the effects of word frequency and/or imageability in the two visual fields/hemispheres. Remarkably, both models comply with the principle of parsimony, although on two different grounds: the *callosal relay – single orthographic lexicon* model adopts a cognitive standpoint, and aims for the explanation that assumes the least amount of processing modules (see for example Gerrans & Stone, 2008). On the other hand, the *direct access – two orthographic lexicons* framework derives from neuropsychology, and it complies with the idea that - from a neurobiological point of view - it is unlikely that the LH is hard-wired to implement such a recent evolutionarily function as reading (Marie, 1897). Remarkably, recent Magnetoencephalography data suggests that both *direct access* and *callosal relay* phenomena co-exist at the neural level (Chu & Meltzer, 2019). However, the relative contribution of these mechanisms in giving rise to the visual field effect and its interaction with psycholinguistic variables has not been assessed.

In Experiment 1, the relative contribution of the two frameworks was evaluated by exploring the extent to which the visual field effect interacts with word length, orthographic neighborhood, word frequency and imageability. The observation of a smaller frequency effect for words presented to the LVF/RH than to the RVF/LH (coupled with the lack of significant interactions between visual fields and word length and orthographic neighborhood in the direction anticipated by the *callosal relay – single orthographic lexicon* model) suggests that the visual field effect is more effectively explained by the *direct access – two orthographic lexicons* framework. The present results could be framed in light of the broad debate in cognitive neuroscience on whether the dominance of the LH over the RH for reading is *absolute* - i.e., the RH is word blind - or *relative* - i.e., the RH is simply less proficient than the LH in orthographic processing- (Bonandrini et al., 2020; Dejerine, 1892; Gazzaniga & Sperry, 1967; Luzzatti, 2003; Luzzatti et al., 1998; Rutherford & Lutz, 2004; Saffran et al., 1980; Saffran & Coslett, 1998). In this scenario, the present results would support the idea that the RH encodes a certain amount of orthographic representations and, therefore, the nature of the dominance of the LH over the RH for reading could be *relative*, rather than *absolute* (Rutherford & Lutz, 2004). This result surely complies with evidence of residual reading abilities in patients with Deep Dyslexia (Coltheart, 1980, 2000; Saffran et al., 1980) and Pure Alexia (Bonandrini et al., 2020; Coslett & Saffran, 1989; Coslett & Saffran, 1994; Saffran &

Coslett, 1998), as well as with evidence of RH reading in split-brain patients (Baynes et al., 1992; Gazzaniga & Hillyard, 1971; Levy & Trevarthen, 1977; Reuter-Lorenz & Baynes, 1992; Zaidel, 1983) and invites to deepen the exploration of the role of the RH in giving rise to spared reading abilities in acquired reading disorders. Still, the literature complying with the *callosal relay – single orthographic lexicon* model (Barca et al., 2011; Ellis, 2004; Ellis et al., 1988; Whitney, 2001; Whitney, 2008; Whitney & Lavidor, 2005) calls for a cautious interpretation of the present data. Our findings are indeed insufficient to completely rule out the possibility that some differences in pre-lexical processing exist between hemispheres. In other words, the present data point towards the idea that the primary *locus* of the visual field effect could be lexical, but this doesn't necessarily imply a *single locus* for such effect. This is in line with recent proposals suggesting that while stimuli projected to the RVF/LH are processed along a homolateral pathway in the LH, stimuli projected to the LVF-RH are both transferred to the LH (via an interhemispheric splenial pathway connecting the right and left Medial Occipital Gyri) and selectively processed by the RH homologue (Chu & Meltzer, 2019) of the so-called Visual Word Form Area (Cohen et al., 2000). Accordingly, both neurocognitive processes at the pre-lexical and lexical level could contribute to giving rise to the visual field effect. Further research will be necessary to explore the extent to which - in line with the present findings - lexical processes consistently play a more prominent role than pre-lexical processes in this regard.

4.2 A role for discriminability

At first glance, the direction of the visual field-by frequency interaction described in Experiment 1 might look surprising. Intuitively, one might expect the word frequency effect to be stronger for stimuli projected in the LVF/RH than in the RVF/LH, by virtue of dramatically worse performance in the LVF/RH than in the RVF/LH for infrequent words, coupled with comparable performance across hemispheres for frequent words (Coltheart, 1980; Luzzatti, 2003; Luzzatti et al., 1998). More broadly, the literature suggests that a relatively small frequency effect is a hallmark of proficient reading and extensive exposure to reading material (see for instance Brysbaert et al., 2018). The results of Experiment 1, instead, point towards a smaller frequency effect in the LVF/RH compared to the RVF/LH. However, the contradiction between the well-established frequency effect-reading performance relationship and the present data is just apparent: in both hemispheres, the relationship between overall RTs (averaged between high- and low- frequency trials) and the magnitude of the frequency effect is in the same – positive - direction (ρ_{RVF}= 0.305; ρ_{LVF}= 0.129), although arguably stronger in the RVF/LH than in the LVF/RH. In other words, in both hemispheres the greater the reading proficiency (i.e., the smaller the overall RTs), the smaller the effect of word frequency. This suggests that the link between reading performance and the magnitude of the frequency effect is not qualitatively different in the two hemispheres. Rather, these data highlight that the mechanisms of lexical activation differ in the two hemispheres. The results of the computational Experiment 2 can guide the interpretation of this result. In Experiment 2, efficient learning of orthographic knowledge in the LH was simulated through the *Naïve Discriminative Learning* approach (Baayen et al., 2011; Milin et al., 2017), that allows the simulation of the stable state (Danks, 2003) of a learning process under the Rescorla-Wagner law (1972). To simulate the RH, we disrupted the distinctiveness of the connection weights from pre-lexical orthographic cues (letters and bigrams) to orthographic output nodes (words). In cognitive terms, disturbing such connection weights implies disturbing the distinctiveness of the association between pre-lexical cues and lexical outcomes, by all means making the activation of lexical/semantic units given a set of orthographic cues less specific (or "more entangled"). The simulations revealed that the less distinctive the connections between orthographic cues and lexical/semantic output units were made (by the addition of significant amount of noise), the higher the simulated visual field effect was, and the more the resulting frequency effect diminished in size. This qualifies discriminability as a possible mechanism giving rise to the visual field effect and its interaction with the word frequency effect. In other words, associations between orthographic cues and lexical/semantic outcomes would be highly distinctive in the LH (as testified by a sizeable processing advantage for frequent words over infrequent words), thus resulting - for each incoming stimulus - in the specific activation of the corresponding output nodes. Conversely, associations between orthographic cues and lexical/semantic outcomes in the RH would be less distinctive (as testified by the relatively small processing advantage for frequent words over infrequent ones), thus yielding - for each incoming stimulus - the activation of a number of different candidate orthographic output nodes, resulting in slower and less efficient performance at the behavioral level. Noteworthy, simulation of hemispheric differences in orthographic processing was achieved not by simply weakening cue-outcome associations in the RH, but by making them less distinctive. To the best of the authors' knowledge, the present implementation represents the most compact computational model capable of simulating the visual field effect. Indeed, previous computational approaches developed to model the visual field effect were characterized by relatively complex theory-driven architectures (Weems & Reggia, 2004; Whitney, 2001; Whitney, 2008; Whitney & Lavidor, 2005). It is important to highlight that the simulations described in this study do not represent a model of the ultimate biological cause of the visual field effect and of the compression of the word frequency effect in the RH. Rather, they offer a computational formalization of a putative cognitive phenomenon (i.e., less distinctiveness of cue-outcome associations in the RH than in the LH) - likely occurring as a result of an external biological cause - capable of producing the visual field effect and its interaction with word frequency at the behavioral level. In this context, the noise introduced in the model represents the means through which the hypothesis of the less distinctiveness of cue-outcome associations in the RH than in the LH was tested, not the alleged ultimate cause of such entangled cue-outcome associations. In this regard, if some alternative perturbation of the model could produce the same (or even a more marked) reduction in the distinctiveness of cue-outcome associations in the RH, nothing would change in the cognitive interpretation of the phenomenon, as long as the distinctiveness of cue-outcome associations (and lack thereof in the RH) explains the smaller word frequency effect in the RH than in the LH. More broadly, such lack of distinctiveness in cue-outcome associations in the RH could be the result of a less efficient learning process in the RH, or rather represent a less efficient access mechanism, with these two different interpretations being virtually indistinguishable at the behavioral level. The present data are indeed insufficient to distinguish these two mediating processes.

Regardless of whether it acts by limiting learning or by limiting orthographic access, the ultimate biological cause of the poorly distinctive connections between orthographic cues and lexical/semantic output units in the RH remains unknown. Critically, this phenomenon must be confined to language material, as evidence suggests that the ventral visual pathways in the RH accurately perform frequency-based object discrimination (Zannino et al., 2011). One possibility in this regard is constituted by inter-hemispheric inhibition exerted by the LH on the RH (Cook, 1984; Landis et al., 1983; van der Knaap & van der Ham, 2011). This mechanism might both cause inefficient learning in the RH and limit access to RH orthographic output nodes at the end of the learning process. On the other hand, the greater efficiency of the LH pathway than the RH one for reading could be due to the fact that the binding between lexical orthographic representations and pre-existing lexical phonological and semantic knowledge derived from spoken language (which is already left-lateralized before reading development starts; Sowman et al., 2014; Ziegler et al., 2014) is mediated by more efficiently connected brain networks in the LH than in the RH

(Behrmann & Plaut, 2015; Plaut & Behrmann, 2011). Most likely, the poorly distinctive connections between orthographic cues and lexical/semantic outputs in the RH could be due to both mechanisms: lateralization of spoken language and efficiency of connections with language areas might determine the way the two hemispheres respond to orthographic stimuli during the early stages of reading acquisition, and interhemispheric inhibition would progressively maximize the advantage of the LH over the RH.

In any case, although further empirical evidence will be required to shed light on this interpretation, the present evidence suggests a link between the discriminative processes underlying storage/retrieval of lexical orthographic information and the specialization of the neural correlates of orthographic processing, for which the left infero-temporal complex known as visual word form area (e.g., Cohen et al., 2000; Cohen et al., 2002; McCandliss et al., 2003; Dehaene & Cohen, 2011) is meant to play a crucial role. In this regard, it is possible to hypothesize discriminative learning as a domain-general mechanism adopted by infero-temporal cortices (see for instance Seidler et al., 2021), providing the computational ground for orthographic processing, with the specificity for language material provided by the unique convenient positioning of this area in the LH, which is already specialized in language processing before reading development starts (Sowman et al., 2014; Ziegler et al., 2014). The comparatively poorer outcome of discriminative learning for orthographic stimuli in the RH could be due to more inefficient connections with the rest of the language system and/or to direct inhibitions from the LH. This interpretation - we believe - could potentially inform future neuroimaging studies exploring the relationship between discriminative learning and the activity of the visual word form system.

4.3 Methodological implications

It is worthy to note that Experiment 1 clearly shows that the visual field effect is biased by psycholinguistic variables. This suggests - somewhat unsurprisingly - that laterality measures based on the visual field effect do not directly reflect invariant properties of functional organization of mind and brain. Rather, these measures represent how the psycholinguistic processes engaged by processing of a very specific pool of stimuli differ between hemispheres. As one of the main purposes of lateralized reading paradigms is to provide a tool (the visual field effect) to measure functional laterality, results of Experiment 1 suggest that steps should be taken to minimize the chance for functional laterality measures to be biased by psycholinguistic factors. One possibility in this regard could be to standardize the levels of psycholinguistic factors across studies (i.e., adopting a relatively fixed range of values for each given psycholinguistic variable).

A more feasible alternative in this direction could entail, rather than considering the "pure" visual field effect, the adoption of lateralization measures based on the comparison of the magnitude of psycholinguistic effects between hemispheres, similarly to the approach proposed by Ellis (2004) and Ellis et al. (1988) for pre-lexical variables.

In any case, results of Experiment 1 suggest that divided visual field reading techniques can effectively be adopted to discriminate between populations displaying different functional lateralization patterns. In Experiment 1, left-handed participants were associated with better performance than right-handers for words projected to the LVF/RH, which is in line with the idea that left-handed individuals display less pronounced LH dominance than right-handers (Branch et al., 1964; Pujol et al., 1999). Remarkably, none of the interactions between visual field/hemisphere and psycholinguistic variables further interacted with hand preference group, indicating that psycholinguistic processes are unlikely to bias functional lateralization estimates obtained by populations characterized by differently patterns of functional lateralization for orthographic processing. This suggests that, once overall differences in functional hemispheric asymmetries are accounted for (i.e., captured by the hand-preference group variable), no further qualitative differences arise between left- and right-handers in the cognitive mechanisms that underly orthographic processes in the two cerebral hemispheres.

5. Conclusions

The present work suggests that the visual field effect in lateralized reading primarily reflects hemispheric differences in how lexical activation unfolds, as anticipated by the *direct access - two orthographic lexicons* framework. Our simulations based on the *Naïve Discriminative Learning* approach suggest that the visual field effect could be due to less distinctive connections (i.e., learned to a lesser extent/more difficult to activate) between orthographic cues and lexical/semantic output units in the RH than in the LH.

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Declarations of interest

None.

References

Ablinger, I., & Domahs, F. (2009). Improved single-letter identification after whole-word training in pure alexia. *Neuropsychological Rehabilitation, 19*(3), 340-363. https://doi.org/10.1080/09602010802204000

Andrews, S. (1992). Frequency and neighborhood effects on lexical access: Lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(2), 234-254. https://doi.org/10.1037/0278-7393.18.2.234

Arppe, A., Hendrix, P., Milin, P., Baayen, R. H., Sering, T., & Shaoul, C. (2015). ndl: Naive discriminative learning. https://cran.r-project.org/web/packages/ndl/ndl.pdf

Baayen, R. H. (2008). *Analyzing linguistic data: a practical introduction to statistics using R*. Cambridge: Cambridge University Press,.

Baayen, R. H. (2010). *Demythologizing the word frequency effect: A discriminative learning perspective. The Mental Lexicon, 5*(3), 436-461. https://doi.org/10.1075/ml.5.3.10baa

Baayen, R. H., Milin, P., Đurđević, D. F., Hendrix, P., & Marelli, M. (2011). An amorphous model for morphological processing in visual comprehension based on naive discriminative learning. *Psychological Review*, *118*(3), 438. https://doi.org/10.1037/a0023851

Babkoff, H., & Ben-Uriah, Y. (1983). Lexical decision time as a function of visual field and stimulus probability. *Cortex*, *19*(1), 13-30. https://doi.org/10.1016/s0010-9452(83)80047-1

Barca, L., Cornelissen, P., Simpson, M., Urooj, U., Woods, W., & Ellis, A. W. (2011). The neural basis of the right visual field advantage in reading: an MEG analysis using virtual electrodes. *Brain and Language*, *118*(3), 53-71. https://doi.org/10.1016/j.bandl.2010.09.003

Bates, D., Maechler, M., Bolker, B., & Walker, S. (2015). lme4: Linear mixed-effects models using Eigen and S4. R package version 1.1-9 http://CRAN. *R-project. org/package= lme4*.

Baynes, K., Tramo, M. J., & Gazzaniga, M. S. (1992). Reading with a limited lexicon in the right hemisphere of a callosotomy patient. *Neuropsychologia*, *30*(2), 187-200. https://doi.org/10.1016/0028-3932(92)90027-j

Behrmann, M., & Plaut, D. C. (2015). A vision of graded hemispheric specialization. *Annals of the New York Academy of Sciences 1359*, 30-46. https://doi.org/10.1111/nyas.12833

Bonandrini, R., Veronelli, L., Licciardo, D., Caporali, A., Judica, E., Corbo, M., & Luzzatti, C. (2020). Can the right hemisphere read? A behavioral and disconnectome study on implicit reading in a patient with pure alexia. *Neurocase*, *26*(6), 321-327. https://doi.org/10.1080/13554794.2020.1830118

Bouhali, F., de Schotten, M. T., Pinel, P., Poupon, C., Mangin, J. F., Dehaene, S., & Cohen, L. (2014). Anatomical connections of the visual word form area. *Journal of Neuroscience, 34*(46), 15402-15414. https://doi.org/10.1523/JNEUROSCI.4918-13.2014

Bourne, V. J. (2006). The divided visual field paradigm: methodological considerations. *Laterality*, *11*(4), 373-393. https://doi.org/10.1080/13576500600633982

Branch, C., Milner, B., & Rasmussen, T. (1964). Intracarotid sodium amytal for the lateralization of cerebral speech dominance: observations in 123 patients. *Journal of Neurosurgery*, *21*(5), 399-405. https://doi.org/10.3171/jns.1964.21.5.0399

Brysbaert, M. (1994). Interhemispheric transfer and the processing of foveally presented stimuli. *Behavioural Brain Research*, *64*(1-2), 151-161. https://doi.org/10.1016/0166-4328(94)90127-9

Brysbaert, M., & d'Ydewalle, G. (1990). Tachistoscopic presentation of verbal stimuli for assessing cerebral dominance: reliability data and some practical recommendations. *Neuropsychologia*, *28*(5), 443-455. https://doi.org/10.1016/0028-3932(90)90071-U

Brysbaert, M., Mandera, P., & Keuleers, E. (2018). The word frequency effect in word processing: An updated review. Current Directions in Psychological Science, *27(1)*, 45-50. https://doi.org/10.1177/096372141772752

Brysbaert, M., Vitu, F., & Schroyens, W. (1996). The right visual field advantage and the optimal viewing position effect: On the relation between foveal and parafoveal word recognition. *Neuropsychology*, *10*(3), 385-395. https://doi.org/10.1037/0894-4105.10.3.385

Bub, D. N., & Lewine, J. (1988). Different modes of word recognition in the left and right visual fields. *Brain and Language, 33*(1), 161-188. https://doi.org/10.1016/0093-934X(88)90060-0

Cai, Q., Paulignan, Y., Brysbaert, M., Ibarrola, D., & Nazir, T. A. (2010). The left ventral occipito-temporal response to words depends on language lateralization but not on visual familiarity. Cerebral Cortex, *20(5)*, 1153-1163. https://doi.org/10.1093/cercor/bhp175

Chiarello, C., Senehi, J., & Soulier, M. (1986). Viewing conditions and hemisphere asymmetry for the lexical decision. *Neuropsychologia*, *24*(4), 521-529. https://doi.org/10.1016/0028-3932(86)90096-5

Chiarello, C., Shears, C., Liu, S., & Kacinik, N. A. (2005). Influence of word class proportion on cerebral asymmetries for high- and low-imagery words. *Brain and Cognition*, *57*(1), 35-38. https://doi.org/10.1016/j.bandc.2004.08.024

Chu, R. K., & Meltzer, J. A. (2019). Interhemispheric connectivity during lateralized lexical decision. *Human Brain Mapping*, *40*(3), 818-832. https://doi.org/10.1002/hbm.24414

Cohen, L., Dehaene, S., Naccache, L., Lehéricy, S., Dehaene-Lambertz, G., Hénaff, M. A., & Michel, F. (2000). The visual word form area: spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain*, *123 (Pt 2)*, 291-307. https://doi.org/10.1093/brain/123.2.291

Cohen, L., Lehéricy, S., Chochon, F., Lemer, C., Rivaud, S., & Dehaene, S. (2002). Language-specific tuning of visual cortex? Functional properties of the Visual Word Form Area. *Brain, 125*(5), 1054-1069. https://doi.org/10.1093/brain/awf094

Coltheart, M. (1980). Deep dyslexia: a right-hemisphere hypothesis. In M. Coltheart, K. Patterson, & J. C. Marshall (Eds.), *Deep Dyslexia* (pp. 326–380). London: Routledge and Kegan Paul.

Coltheart, M. (2000). Deep dyslexia is right-hemisphere reading. *Brain and Language*, *71*(2), 299-309. https://doi.org/10.1006/brln.1999.2183

Coltheart, M., & Rastle, K. (1994). Serial processing in reading aloud: Evidence for dual-route models of reading. *Journal of Experimental Psychology: Human Perception and Performance*, *20*(6), 1197-1211. https://doi.org/10.1037/0096-1523.20.6.1197

Coltheart, M., Rastle, K., Perry, C., Langdon, R., & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*(1), 204. https://doi.org/10.1037/0033-295X.108.1.204

Cook, N. D. (1984). Homotopic callosal inhibition. *Brain and Language*, *23*(1), 116-125. https://doi.org/10.1016/0093-934X(84)90010-5

Coslett, H. B., & Saffran, E. M. (1989). Evidence for preserved reading in 'pure alexia'. *Brain*, *112 (Pt 2)*, 327-359. https://doi.org/10.1093/brain/112.2.327

Coslett, H. B., & Saffran, E. M. (1994). Mechanisms of implicit reading in alexia. In M. Farah & G. Ratcliff (Eds.), *The neuropsychology of high-level vision* (pp. 299–330). Hillsdale: Lawrence Erlbaum Associates.

Crepaldi, D., Keuleers, E., Mandera, P., & Brysbaert, M. (2013). SUBTLEX-IT. In.

Danks, D. (2003). Equilibria of the Rescorla–Wagner model. *Journal of Mathematical Psychology*, *47*(2), 109-121. https://doi.org/10.1016/S0022-2496(02)00016-0

Day, J. (1977). Right-hemisphere language processing in normal right-handers. *Journal of Experimental Psychology: Human Perception and Performance*, *3*(3), 518-528. https://doi.org/10.1037//0096-1523.3.3.518

De Clercq, P., & Brysbaert, M. (2020). The influence of word valence on the right visual field advantage in the VHF paradigm: time to adjust the expectations. *Laterality*, *25*(5), 537-559. https://doi.org/10.1080/1357650X.2020.1736091

De Rosario-Martinez, H. (2013). phia: Post-hoc interaction analysis. *R package version 0.1-3*.

Dehaene, S., & Cohen, L. (2011). The unique role of the visual word form area in reading. *Trends in Cognitive Sciences, 15*(6), 254-262. https://doi.org/10.1016/j.tics.2011.04.003

Dehaene, S., Cohen, L., Morais, J., & Kolinsky, R. (2015). Illiterate to literate: behavioural and cerebral changes induced by reading acquisition. *Nature Reviews Neuroscience, 16*(4), 234-244. https://doi.org/10.1038/nrn3924

Dejerine, J. (1892). Contribution à l'étude anatomopathologique et clinique des différents variétés de cécité verbale. *Mémoires de la Société de Biologie*, *4*, 61-90.

Ellis, A. W. (2004). Length, formats, neighbours, hemispheres, and the processing of words presented laterally or at fixation. *Brain and Language*, *88*(3), 355-366. https://doi.org/10.1016/S0093-934X(03)00166-4

Ellis, A. W., Young, A. W., & Anderson, C. (1988). Modes of word recognition in the left and right cerebral hemispheres. *Brain and Language*, *35*(2), 254-273. https://doi.org/10.1016/0093-934X(88)90111-3

Eviatar, Z., Menn, L., & Zaidel, E. (1990). Concreteness: nouns, verbs, and hemispheres. *Cortex*, *26*(4), 611-624. https://doi.org/10.1016/S0010-9452(13)80310-3

Gazzaniga, M. S., Bogen, J. E., & Sperry, R. W. (1962). Some functional effects of sectioning the cerebral commissures in man. *Proceedings of the National Academy of Sciences*, *48*(10), 1765-1769. https://doi.org/10.1073/pnas.48.10.1765

Gazzaniga, M. S., & Hillyard, S. A. (1971). Language and speech capacity of the right hemisphere. *Neuropsychologia*, *9*(3), 273-280. https://doi.org/10.1016/0028-3932(71)90022-4

Gazzaniga, M. S., & Sperry, R. W. (1967). Language after section of the cerebral commissures. *Brain*, *90*(1), 131-148. https://doi.org/10.1093/brain/90.1.131

Gerrans, P., & Stone, V. E. (2008). Generous or parsimonious cognitive architecture? Cognitive neuroscience and theory of mind. *The British Journal for the Philosophy of Science*, *59*(2), 121-141. doi:10.1093/bjps/axm038

Gerrits, R., De Clercq, P., Verhelst, H., & Vingerhoets, G. (2020). Evaluating the performance of the visual half field paradigm as a screening tool to detect right hemispheric language dominance. *Laterality*, *25*(6), 722-739. https://doi.org/10.1080/1357650X.2020.1854279

Goslin, J., Galluzzi, C., & Romani, C. (2014). PhonItalia: a phonological lexicon for Italian. *Behavior Research Rethods*, *46*(3), 872-886. https://doi.org/10.3758/s13428-013-0400-8

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: a multiple read-out model. *Psychological Review,* *103*(3), 518. https://psycnet.apa.org/doi/10.1037/0033-295X.103.3.518

Hausmann, M., Brysbaert, M., van der Haegen, L., Lewald, J., Specht, K., Hirnstein, M., . . . Mohr, C. (2019). Language lateralisation measured across linguistic and national boundaries. *Cortex*, *111*, 134-147. https://doi.org/10.1016/j.cortex.2018.10.020

Hunter, Z. R., & Brysbaert, M. (2008). Visual half-field experiments are a good measure of cerebral language dominance if used properly: evidence from fMRI. *Neuropsychologia*, *46*(1), 316-325. https://doi.org/10.1016/j.neuropsychologia.2007.07.007

Iacoboni, M., & Zaidel, E. (1996). Hemispheric independence in word recognition: evidence from unilateral and bilateral presentations. *Brain and Language*, *53*(1), 121-140. https://doi.org/10.1006/brln.1996.0040

Kim, H. (1994). Distributions of hemispheric asymmetry in left-handers and right-handers: Data from perceptal asymmetry studies. *Neuropsychology*, *8*(2), 148-159. https://psycnet.apa.org/doi/10.1037/0894-4105.8.2.148

Landis, T., Regard, M., Graves, R., & Goodglass, H. (1983). Semantic paralexia: A release of right hemispheric function from left hemispheric control? *Neuropsychologia*, *21*(4), 359-364. https://doi.org/10.1016/0028-3932(83)90022-2

Lavidor, M., Babkoff, H., & Faust, M. (2001). Analysis of standard and non-standard visual word format in the two hemispheres. *Neuropsychologia*, *39*(4), 430-439. https://doi.org/10.1016/s0028-3932(00)00125-1

Lavidor, M., & Ellis, A. W. (2003). Interhemispheric integration of letter stimuli presented foveally or extra-foveally. *Cortex*, *39*(1), 69-83. https://doi.org/10.1016/s0010-9452(08)70075-3

Lavidor, M., & Walsh, V. (2003). A magnetic stimulation examination of orthographic neighborhood effects in visual word recognition. *Journal of Cognitive Neuroscience*, *15*(3), 354-363. https://doi.org/10.1162/089892903321593081

Leiber, L. (1976). Lexical decisions in the right and left cerebral hemispheres. *Brain and Language*, *3*(3), 443-450. https://doi.org/10.1016/0093-934x(76)90038-9

Levy, J., & Trevarthen, C. (1977). Perceptual, semantic and phonetic aspects of elementary language processes in split-brain patients. *Brain*, *100 Pt 1*, 105-118. https://doi.org/10.1093/brain/100.1.105

Luzzatti, C. (2003). Optic aphasia and pure alexia: contribution of callosal disconnection syndromes to the study of lexical and semantic representation in the right hemisphere. In Zaidel, E., & Iacoboni, M. (Eds.), *The Parallel Brain: The Cognitive Neuroscience of the Corpus Callosum* (pp. 479-499). Cambridge, MA: MIT Press.

Luzzatti, C., Rumiati, R. I., & Ghirardi, G. (1998). A functional model of visuo-verbal disconnection and the neuroanatomical constraints of optic aphasia. *Neurocase*, *4*(1), 71-87. https://doi.org/10.1080/13554799808410609

Marie, P. (1897). L'évolution du langage considérée au point de vue de l'étude de l'aphasie. *La Presse Médicale*, *5, 397-399*.

McCandliss, B. D., Cohen, L., & Dehaene, S. (2003). The visual word form area: expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences,* *7*(7), 293-299. https://doi.org/10.1016/S1364-6613(03)00134-7

McClelland, J. L., & Rumelhart, D. E. (1981). *An interactive activation model of context effects in letter perception: I. An account of basic findings. Psychological review, 88*(5), 375. https://psycnet.apa.org/doi/10.1037/0033-295X.88.5.375

Mergen, F., & Kuruoglu, G. (2021). Lateralization of lexical processing in monolinguals and bilinguals. *International Journal of Bilingualism*, *25*(6), 1497-1509. https://doi.org/10.1177%2F13670069211018842

Milin, P., Feldman, L. B., Ramscar, M., Hendrix, P., & Baayen, R. H. (2017). Discrimination in lexical decision. *PloS one*, *12*(2), e0171935. https://doi.org/10.1371/journal.pone.0171935

Mills, R., Woodhead, Z. V., & Parker, A. J. (2022). Orthographic neighborhood effects during lateralized lexical decision are abolished with bilateral presentation. *Journal of Experimental Psychology: Human Perception and Performance*, *48*(5):481-496. https://psycnet.apa.org/doi/10.1037/xhp0000997

Mishkin, M. (1949). *Word recognition as a function of retinal locus.* McGill University. McGill University Library.

Mishkin, M., & Forgays, D. G. (1952). Word recognition as a function of retinal locus. *Journal of Experimental Psychology*, *43*(1), 43-48. https://doi.org/10.1037/h0061361

Olk, B., & Hartje, W. (2001). The bilateral effect: callosal inhibition or intrahemispheric competition? *Brain and Cognition*, *45*(3), 317-324. https://doi.org/10.1006/brcg.2000.1258

Perea, M., Acha, J., & Fraga, I. (2008). Lexical competition is enhanced in the left hemisphere: evidence from different types of orthographic neighbors. *Brain and Language*, *105*(3), 199-210. https://doi.org/10.1016/j.bandl.2007.08.005

Plaut, D. C., & Behrmann, M. (2011). Complementary neural representations for faces and words: a computational exploration. *Cognitive Neuropsychology*, *28*(3-4), 251-275. https://doi.org/10.1080/02643294.2011.609812

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103*, 56 –115. https://doi.org/10.1037/0033-295x.103.1.56

Pujol, J., Deus, J., Losilla, J. M., & Capdevila, A. (1999). Cerebral lateralization of language in normal left-handed people studied by functional MRI. *Neurology*, *52*(5), 1038-1043. https://doi.org/10.1212/wnl.52.5.1038

Rescorla, R. A., & Wagner, A. R. (1972). A theory of pavlovian conditioning: variations in the effectiveness of reinforcement and nonreinforcement. In A. H. Black & W. F. Prokasy (Eds.), *CLASSICAL CONDITIONING II: Current Theory and Research* (pp. 64-99). New York: Appleton-Century-Crofts.

Reuter-Lorenz, P. A., & Baynes, K. (1992). Modes of lexical access in the callosotomized brain. *Journal of Cognitive Neuroscience*, *4*(2), 155-164. https://doi.org/10.1162/jocn.1992.4.2.155

Rutherford, B. J., & Lutz, K. T. (2004). Conflicting strategies and hemispheric suppression in a lexical decision task. *Brain and Cognition*, *55*(2), 387-391. https://doi.org/10.1016/j.bandc.2004.02.055

Saffran, E. M., Bogyo, L. C., Schwartz, M. F., & Marin, O. S. M. (1980). Does deep dyslexia reflect right-hemisphere reading? In M. Coltheart, K. Patterson, & J. C. Marshall (Eds.), *Deep Dyslexia* (pp. 381-406). London: Routledge and Kegan Paul.

Saffran, E. M., & Coslett, H. B. (1998). Implicit vs. letter-by-letter reading in pure alexia: A tale of two systems. *Cognitive Neuropsychology*, *15*(1-2), 141-165. https://doi.org/10.1080/026432998381249

Seider, T. R., Porges, E. C., Woods, A. J., & Cohen, R. A. (2021). An fMRI study of age-associated changes in basic visual discrimination. *Brain Imaging and Behavior, 15*(2), 917-929. https://doi.org/10.1007/s11682-020-00301-x

Sowman, P. F., Crain, S., Harrison, E., & Johnson, B. W. (2014). Lateralization of brain activation in fluent and non-fluent preschool children: a magnetoencephalographic study of picture-naming. *Frontiers in Human Neuroscience*, *8*, 354. https://doi.org/10.3389/fnhum.2014.00354

Tomkins, B. (2020). Right visual field advantage for lexical decision dependent on stimulus size and visibility: Evidence for an early processing account of hemispheric asymmetry. *Laterality*, 26(5), 539-563. https://doi.org/10.1080/1357650X.2020.1856126

Van der Haegen, L., Cai, Q., Seurinck, R., & Brysbaert, M. (2011). Further fMRI validation of the visual half field technique as an indicator of language laterality: a large-group analysis. *Neuropsychologia*, *49*(10), 2879-2888. https://doi.org/10.1016/j.neuropsychologia.2011.06.014

Van der Knaap, L. J., & van der Ham, I. J. (2011). How does the corpus callosum mediate interhemispheric transfer? A review. *Behavioural Brain Research*, *223*(1), 211-221. https://doi.org/10.1016/j.bbr.2011.04.018

Van Heuven, W. J., Dijkstra, T., & Grainger, J. (1998). *Orthographic neighborhood effects in bilingual word recognition. Journal of memory and language, 39*(3), 458-483. https://doi.org/10.1006/jmla.1998.2584

Van Heuven, W. J., Mandera, P., Keuleers, E., & Brysbaert, M. (2014). SUBTLEX-UK: a new and improved word frequency database for British English. *Quarterly Journal of Experimental Psychology*, *67*(6), 1176-1190. https://doi.org/10.1080/17470218.2013.850521

Waldie, K. E., & Mosley, J. L. (2000a). Developmental trends in right hemispheric participation in reading. *Neuropsychologia*, *38*(4), 462-474. https://doi.org/10.1016/s0028-3932(99)00091-3

Waldie, K. E., & Mosley, J. L. (2000b). Hemispheric specialization for reading. *Brain and Language*, *75*(1), 108-122. https://doi.org/10.1006/brln.2000.2346

Weems, S. A., & Reggia, J. A. (2004). Hemispheric specialization and independence for word recognition: a comparison of three computational models. *Brain and Language*, *89*(3), 554-568. https://doi.org/10.1016/j.bandl.2004.02.001

Whitney, C. (2001). How the brain encodes the order of letters in a printed word: the SERIOL model and selective literature review. *Psychonomic Bulletin & Review*, *8*(2), 221-243. https://doi.org/10.3758/bf03196158

Whitney, C. (2008). Supporting the serial in the SERIOL model. *Language and Cognitive Processes*, *23*(6), 824-865. https://doi.org/10.1080/01690960701828202

Whitney, C., & Lavidor, M. (2005). Facilitative orthographic neighborhood effects: the SERIOL model account. *Cognitive Psychology* *51*(3), 179-213. https://doi.org/10.1016/j.cogpsych.2005.07.001

Willemin, J., Hausmann, M., Brysbaert, M., Dael, N., Chmetz, F., Fioravera, A., . . . Mohr, C. (2016). Stability of right visual field advantage in an international lateralized lexical decision task irrespective of participants' sex, handedness or bilingualism. *Laterality*, *21*(4-6), 502-524. https://doi.org/10.1080/1357650X.2015.1130716

Yarkoni, T., Balota, D., & Yap, M. (2008). Moving beyond Coltheart's N: a new measure of orthographic similarity. *Psychonomic Bulletin & Review,*, *15*(5), 971-979. https://doi.org/10.3758/PBR.15.5.971

Young, A. W., & Ellis, A. W. (1985). Different methods of lexical access for words presented in the left and right visual hemifields. *Brain and Language*, *24*(2), 326-358. https://doi.org/10.1016/0093-934X(85)90139-7

Zaidel, E. (1982). Reading by the disconnected right hemisphere: An aphasiological perspective. In Y. Zotterman (Ed.), Dyslexia: Neuronal, Cognitive & Linguistic Aspects (pp. 67-91). Oxford: Pergamon.

Zaidel, E. (1983). A response to Gazzaniga. Language in the right hemisphere, convergent perspectives. *American Psychologist*, *38*(5), 542-546. https://psycnet.apa.org/doi/10.1037/0003-066X.38.5.542

Zaidel, E., & Peters, A. M. (1981). Phonological encoding and ideographic reading by the disconnected right hemisphere: two case studies. *Brain and Language*, *14*(2), 205-234. https://doi.org/10.1016/0093-934X(81)90077-8

Zannino, G. D., Barban, F., Macaluso, E., Caltagirone, C., & Carlesimo, G. A. (2011). The neural correlates of object familiarity and domain specificity in the human visual cortex: An fMRI study. *Journal of Cognitive Neuroscience,* *23*(10), 2878-2891. https://doi.org/10.1162/jocn.2011.21629

Ziegler, J. C., Perry, C., & Zorzi, M. (2014). Modelling reading development through phonological decoding and self-teaching: implications for dyslexia. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *369*(1634), 1-9. 20120397. https://doi.org/10.1098/rstb.2012.0397