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FACULDADE DE PSICOLOGIA

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Discrimination of orientation contrasts during visual word recognition

Eduardo Guilherme Plath Xavier

MESTRADO INTEGRADO EM PSICOLOGIA

(Secção de Cognição Social Aplicada)

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Dissertação orientada pela Professora Doutora Tânia Fernandes

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Acknowledgments

I would like to thank my advisor, Professor Tânia Fernandes, for accepting me in this project, for always being present and teaching me more than I could have hoped to learn. To Margarida Cipriano, for her help during the preparation and conduction of the experimental sessions. To Tatiana, for her helpful comments. To Catarina, Maria, Rita, Luísa and Carolina, thank you for making writing this thesis a lot more joyful, and making all my writing breaks worthy of the most "insightful" conversations. A sincere thanks to all the participants.

Finally, I would like to thank my parents, my girlfriend, and my friends for their continuous support during all these years. I am truly grateful for everything.

The experimental study conducted under this thesis was supported by the project VOrtEx (ref 28184) funded by Fundação para a Ciência e Tecnologia, FCT, and by FEDER (POR Lisboa 2020 and by the Research Center for Psychological Sciences, CICPSI, of Faculdade de Psicologia da Universidade de Lisboa).

Abstract

To effectively discriminate *mirrored* letters (e.g., *b* and *d*), when learning to read one must overcome *mirror invariance* (an original property of the visual system that treats lateral reflected images as equivalent percepts). Previous studies suggested that mirror invariance might still occur during letter identification, and that in contrast with *nonreversible* letters (which differ from other letters of the script by shape, being orientation an irrelevant feature: f, R), discrimination of *reversible* letters (for which orientation is a diagnostic feature: *d*, *p*, *b*: *N*, *Z*) relies on a specific mechanism of mirror-image suppression.

We explored how orientation contrasts influence discrimination of reversible (b; d; p) and nonreversible (f; r, t) letters during word recognition. In Experiment 1, we adopted a lexical decision task with a *sandwich priming* paradigm, to reduce lexical influences. Lowercase primes differed from uppercase targets (e.g., IDEA) on the critical letter only: *identical* prime (lowercase version of the target: idea); *mirrored* prime (mirror-image of the critical letter: ibea); *rotated* prime (180º plane rotation of the critical letter: ipea); *control* prime (critical letter replaced by a mask: i▒ea). In Experiment 2, we adopted a *same-different* task with masked priming, using the same prime-target conditions. The pattern of results was similar in both experiments. Target decisions for reversible letters was slower when letters were transformed in orientation (mirrored or rotated) relative to control and identical primes. For nonreversible letters, orientation contrasts facilitated target recognition, leading to faster word decisions relative to controls, but slower than identical primes in Experiment 1. Given the similar effects for rotated and mirrored primes, a mechanism of mirror invariance cannot fully explain the present results. We propose that, when visual features are compatible with multiple letter representations, those representations will be activated, leading to competition effects between them (through mutual inhibition). The same principle of recognition-by-components, originally proposed in visual object recognition, seems to apply to letter identification.

Keywords: visual word recognition; abstract letter identity; mirror-image discrimination; orientation contrast; orthographic processing.

Resumo

De forma a discriminar letras reversíveis (e.g., *b* e *d*) eficazmente, durante a aprendizagem da leitura é necessário ultrapassar a *invariância ao espelho* (uma propriedade original do sistema visual que trata reflexos laterais como sendo perceptos equivalentes). Estudos anteriores sugerem que a invariância ao espelho pode ainda ocorrer durante a identificação de letras, e que em contraste com letras *não-reversíveis* (que diferem de outras letras do alfabeto na forma, sendo a sua orientação uma propriedade irrelevante: f, R), a discriminação de letras *reversíveis* (para as quais a orientação é uma propriedade de diagnóstico: d, p, b; N, Z) depende de um mecanismo específico de supressão de imagens em espelho.

Neste estudo, exploramos qual a influência de contrastes de orientação na discriminação de letras reversíveis (b; d; p) e não-reversíveis (f; r; t) durante o reconhecimento de palavras. Na Experiência 1, adotamos uma tarefa de decisão lexical com o paradigma *priming sandwich*, para reduzir influências lexicais. Os primes em minúsculas diferem dos alvos em maiúsculas (e.g., IDEIA) na letra critica apenas: prime *identical* (versão do alvo em minúsculas: ideia); prime *mirrored* (imagem em espelho da letra crítica: ibeia); prime *rotated* (letra crítica rodada no plano 180º: ipeia); condição *control* (letra crítica substituída por uma máscara: i▒eia). Na Experiência 2, adotamos uma tarefa *same-different* com priming mascarado, utilizando as mesmas condições prime-alvo. O padrão de resultados foi semelhante nas duas experiências. A transformação da orientação (imagem-espelho ou rotação) em letras reversíveis resultou em respostas mais lentas relativamente a condição de controlo. Para letras não-reversíveis, os contrastes de orientação facilitaram o reconhecimento do alvo, levando a respostas mais rápidas relativamente à condição de controlo, mas mais lentas do que a condição *identical* na Experiência 1. Dada a semelhança nos efeitos obtidos para ambos os contrastes de orientação, estes resultados não podem ser totalmente explicados segundo um mecanismo de invariância ao espelho. Propomos que, quando os traços visuais são compatíveis com múltiplas representações de letras, estas representações são ativadas, levando a efeitos de competição entre elas (através de mútua inibição). O mesmo princípio de reconhecimento-por-componentes, proposto originalmente no reconhecimento visual de objetos, parece aplicar-se à identificação de letras.

Palavras chave: reconhecimento visual da palavra; representação abstracta de letras; discriminação de imagens em espelho; contrastes de orientação; processamento ortográfico

Resumo alargado

Os modelos actuais de reconhecimento da palavra escrita assumem que a leitura depende do reconhecimento de letras, que se encontram codificadas no sistema cognitivo sob a forma de identidades abstratas, permitindo a sua identificação independentemente de certas alterações na forma (e.g., “A”, “a”, “**𝒜**”, “^{a}” são reconhecidos como a mesma letra). Uma das características de diferenciação de certas letras, presente em alguns sistemas de escrita como no alfabeto Latino, é a sua orientação. Letras *reversíveis* partilham todos os traços e forma visual com outras letras, sendo a orientação a única forma de as diferenciar (e.g., *b, d, p*; *N, Z*). Contrariamente, letras *não-reversíveis,* não partilham todos os traços nem forma visual com outras letras, não sendo a orientação uma característica de diagnóstico para o reconhecimento (e.g., os estímulos “ ɿ ”, “ ɹ ” e “r” são reconhecidos como a mesma letra).

Particularmente, a discriminação de imagens em espelho (e.g., *b* é diferente de *d*) ocorre apenas após a aprendizagem da leitura. Ou seja, antes desta aprendizagem, imagens em espelho (e.g., os pares de letras *b* / *d* e *p* / *q*) são reconhecidas como o mesmo percepto. Esta tendência no processamento visual de objectos é denominada *invariância ao espelho* (Bornstein, Gross, & Wolf, 1978). Estudos anteriores revelam que é de facto a aprendizagem da leitura em sistemas de escrita com símbolos em espelho o principal factor que potencia a capacidade de discriminar este tipo de contraste (e.g., Danziger & Pederson, 1998; Kolinsky et al., 2011). O mesmo não ocorre para a discriminação de rotações no plano das imagens (e.g., *d* é diferente de *p*), sendo o sistema visual inerentemente sensível a este tipo de contraste de orientação (*discriminação de rotações no plano*; Logothetis, Pauls, & Poggio, 1995).

Durante a aprendizagem da leitura, o cérebro sofre várias alterações a nível funcional e estrutural (e.g., Dehaene et al., 2010). Especificamente, McCandliss, Cohen e Dehaene (2003) revêem as evidências para uma região cerebral especializada para o processamento da leitura, denominada *Visual Word Form Area*. No entanto, o surgimento da escrita é relativamente recente (< 5400 anos) para ter possibilitado o desenvolvimento (através de pressão seletiva) de uma região dedicada ao processamento da leitura. A hipótese da *reciclagem neuronal* proposta por Dehaene (2004), prevê que regiões neuronais pré-existentes com funções semelhantes às requeridas por invenções culturais (e.g., linguagem e reconhecimento visual de objetos), e suficientemente plásticas para sofrer reorganização parcial, são "recicladas" de modo a cumprir uma nova função (e.g., escrita), podendo esta reorganização ter impacto sobre funções originais. De facto, embora a discriminação de imagens em espelho surja apenas com a necessidade de discriminar letras reversíveis em sistemas de escrita específicos, após a aprendizagem da leitura este efeito pode ser observado no processamento visual de objetos não-linguísticos (e.g., Kolinsky & Fernandes, 2014).

Apesar da vasta contribuição por parte da literatura acerca do impacto da leitura na percepção visual, os modelos computacionais atuais de reconhecimento da palavra escrita ainda não assumem parâmetros que permitam a computação e previsão de certos efeitos descritos na literatura, tais como o papel específico da discriminação de contrastes de orientação (e.g., imagens em espelho) durante o processamento ortográfico (ver Perea, Moret-Tatay, & Panadero, 2011).

Um dos modelos computacionais de referência no processamento visual de palavras é o *modelo de ativação interactiva* (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Este modelo assume três níveis de processamento, sendo estes compostos por *nodes* (unidades de representação abstrata) para traços, letras e palavras. Estes níveis interagem entre si através de ligações excitatórias e inibitórias, e dentro dos níveis de letras e palavras os *nodes* interagem entre si através de ligações estritamente inibitórias. Quando a activação de um *node* de uma palavra atinge um determinado limiar, dada a apresentação de um estímulo ortográfico, dá-se o reconhecimento dessa palavra. Em contraste, outros modelos computacionais assumem o reconhecimento de palavras como um processo de tomada de decisão derivado da aplicação do teorema de *Bayes*. Neste sentido, dado um determinado input, estes modelos calculam a probabilidade de uma determinada palavra estar presente, com base na amostra recolhida (i.e., output disponível) e conhecimento prévio (e.g., frequência de palavras; e.g., Norris, 2006; Norris & Kinoshita, 2012).

Sendo a invariância ao espelho uma propriedade original do sistema visual, estudos anteriores sugerem que esta propriedade de processamento nunca é inteiramente ultrapassado durante a aprendizagem da leitura, ocorrendo ainda durante o reconhecimento visual de palavras (Duñabeitia, Molinaro, & Carreiras, 2011; Perea, Moret-Tatay, & Panadero, 2011). Dado que apenas letras reversíveis geram uma letra do alfabeto quando transformadas na sua imagem em espelho, Perea e colaboradores (2011) sugerem que a discriminação destas letras depende de um mecanismo específico de supressão de imagens em espelho. Segundo estes autores, letras não-reversíveis são ainda afetadas pela invariância ao espelho, uma vez que não necessitam deste mecanismo (adicional) para serem identificadas. Perea e colaboradores (2011) demonstraram que a transformação de letras reversíveis e não-reversíveis para a sua imagem em espelho, numa tarefa de decisão lexical com priming mascarado, produz efeitos opostos. Especificamente, a apresentação de uma letra reversível em espelho no prime (e.g., “ibeia”) interfere com o reconhecimento do alvo (i.e., inibição da resposta para “IDEIA”), enquanto que a mesma manipulação em letras não-reversíveis facilita o reconhecimento do alvo (e.g., “aɿena” facilita a resposta a “ARENA”).

Neste estudo, testamos se os efeitos descritos (i.e., inibição para letras reversíveis e facilitação para letras não-reversíveis quando transformadas na sua imagem em espelho; Perea et al., 2011) se devem a um mecanismo específico de supressão de imagens em espelho, ou se, de acordo com a proposta de Dehaene (2004), após a aprendizagem da leitura a invariância ao espelho deixa de atuar durante o processamento ortográfico. Neste sentido, propomos que os efeitos descritos por Perea e colaboradores (2011) podem ser explicados à luz dos pressupostos teóricos dos modelos computacionais de reconhecimento da palavra escrita. Para este efeito, desenvolvemos duas experiências adotando um design semelhante ao de Perea e colaboradores (Experiência 3), onde comparamos o impacto de contrastes de orientação no reconhecimento de letras reversíveis (b, d, p) e não-reversíveis (f, r, t). Nas duas experiências deste estudo, adicionamos um segundo contraste de orientação às três condições apresentadas originalmente por Perea e colaboradores (2011). Para cada alvo apresentado em maiúsculas (e.g., IDEIA, letra critica sublinhada) existiam quatro condições de prime (em minúsculas): condição prime *identical* (versão idêntica do alvo: idea); *mirrored* (letra critica transformada na sua versão em espelho: ibeia); *rotated* (letra critica rodada no plano 180º: ipeia); *control* (condição de controlo em que a letra critica foi substituída por uma máscara: i▒eia).

Tendo em conta que o sistema visual é originalmente sensível a rotações no plano (Logothetis et al., 1995), ao adicionar a condição *rotated*, e comparando os efeitos desta condição aos da condição *mirrored*, é possível perceber se os efeitos de priming opostos anteriormente descritos por Perea e colaboradores (2011), para a transformação de letras reversíveis e não-reversíveis na sua versão em espelho (na condição *mirrored*), se devem a um mecanismo específico de invariância ao espelho.

Na Experiência 1 utilizamos uma tarefa de decisão lexical com o paradigma *sandwich priming* (reduzindo efeitos de competição lexical entre diferentes condições de prime; ver Lupker & Davis, 2009). De forma a reduzir possíveis influências lexicais durante o reconhecimento de letras, na Experiência 2 foi adotado um paradigma *same-different* com priming mascarado (cf. Norris & Kinoshita, 2008), garantindo que os resultados obtidos na Experiência 1 se devem a processos a nível pré-lexical (i.e., nível de traços e letras).

O padrão de resultados foi semelhante em ambas as experiências. Como esperado, não se observaram diferenças significativas entre tipos de letra (i.e., reversível e não-reversível) na condição *identical*, produzindo esta condição respostas mais rápidas relativamente à condição *control*. A transformação de orientação (*mirrored* e *rotated*) em letras reversíveis produziu efeitos inibitórios no reconhecimento dos alvos, levando a respostas mais lentas por parte dos participantes em relação a condição de controlo. Contrariamente, os mesmos contrastes de orientação em letras não-reversíveis produziram um efeito facilitador, levando a respostas mais rápidas. Estes resultados não podem ser completamente explicados através de um mecanismo de invariância ao espelho, dado que os mesmos efeitos foram encontrados para transformações de letras na sua versão espelho e para rotações no plano, sendo o sistema visual originalmente sensível a este último contraste de orientação. Os resultados sugerem que os processos envolvidos no reconhecimento de letras seguem os mesmos princípios aplicados ao reconhecimento visual de objetos, sendo afetados da mesma forma por contrastes de orientação, independentemente do tipo de letra (reversível ou não-reversível).

Considerando o modelo de ativação interativa (McClelland & Rumelhart, 1981), os efeitos encontrados podem ser explicados da seguinte forma: os traços e forma visual de letras reversíveis são compatíveis com múltiplas representações abstratas de letras (i.e., *b*, *d*, *p* são compostos pelos mesmos traços e forma visual), levando a que transformação na orientação (*mirrored* e *rotated*) destas letras no prime ativem representações abstratas de letras incompatíveis com a letra crítica presente no alvo, interferindo com o reconhecimento do mesmo devido a efeitos de competição entre letras (entre quais as ligações são estritamente inibitórias). Contrariamente, a transformação da orientação em letras não-reversíveis no prime facilita o reconhecimento da letra crítica no alvo, já que os traços e forma visual destas transformações (e.g., “ ɿ”, “ɹ”) não são compatíveis com nenhuma outra letra do alfabeto a não ser a letra critica original (“r”).

Palavras chave: reconhecimento visual da palavra; representação abstracta de letras; discriminação de imagens em espelho; contrastes de orientação; processamento ortográfico

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1. Introduction

Most models of visual word recognition assume that reading relies on the recognition of letters, coded in the cognitive system in the form of *abstract* identities, that is, unbound to specific letter formats such as case, size, font and position (e.g., “A”, “a”, “𝓐 ” and “^{a}” are all recognized as the same letter). Interestingly, in some scripts (including ours), orientation can be both irrelevant towards letter recognition (e.g., “ ɿ ”, “ ɹ ” and “r” are all perceived as corresponding to the same letter) or it can serve as a diagnostic feature for recognition (e.g., b, d, p and q are all orientation contrasts of the same visual shape but they are perceived as corresponding to different letters). However, the ability to discriminate letters that are lateral reflections of each other (e.g., d / b and q / p) is not an original property of the visual system. In fact, prior to literacy acquisition, lateral reflected images or *mirror images* are perceived as being the same percept, a tendency in visual image processing known as *mirror-image generalization* (or *mirror invariance;* cf. Bornstein, Gross, & Wolf, 1978). Indeed, during the early stages of literacy acquisition, pre-literate children tend to confuse mirrored images, resulting in common mistakes, such as writing their entire name from right to left or confusing the pairs of letters: d / b and q / p (e.g., Fernandes, Leite, & Kolinsky, 2016; Schott, 2007). Moreover, illiterate adults show poor mirror-image discrimination performance in vision-for-perception tasks (e.g., Kolinsky et al., 2011; Pegado et al., 2014). Mirror invariance has also been shown to occur in other primates, octopi, and pigeons (e.g., Logothetis et al., 1995; Rollenhagen & Olson, 2000; Sutherland, 1964). Although seemingly detrimental towards object recognition, this processing tendency plays a pivotal role in the perception of the real world, given that the context or form in which an object is presented should not compromise the ability to recognize it. Animal survivability may depend on the ability to consistently recognize certain objects stored in memory (e.g., threatful predators), regardless of illumination, position, orientation or direction (Sutherland, 1964).

Although many advances have been made since the first computational models of visual word recognition (e.g., McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982), the mechanisms that take part in the early stages of *orthographic* processing (that is, the cognitive computation from pixels, features into abstract letter identities) remain thus far largely undisclosed. Indeed, the parameters proposed by contemporary computational models of visual word recognition are still unable to account for some of the effects reported in empirical studies (Marcet & Perea, 2017). This was precisely the main purpose of the study conducted under this thesis.

Here, I present the rationale for two experiments developed to better understand letter and word recognition. We examined how the visual system processes visual percepts and their features, and computes them into abstract letter identities, during orthographic processing. To this aim, we focused on the role of orientation contrasts during visual word recognition (e.g., *d* is different from *b* and is different from *p*), considering two original properties of the visual system, specifically: mirror invariance and *plane-rotation discrimination*. The latter property refers to the sensitivity of the visual system to orientation contrasts in the picture plane, that is, images that are rotated in the picture plane (e.g., 180º clockwise: as *d* and *p*) are processed by the ventral stream, which is responsible for object recognition, as different percepts (Logothetis et al., 1995; Rollenhagen & Olson, 2000). Using single-cell electrophysiological recordings, Logothetis et al. (1995) showed that specific populations of neurons in the inferior temporal cortex of primates (comparable to ours, and part of the *ventral* visual stream dedicated to the recognition and identification of visual familiar objects; Milner & Goodale, 2008), selectively respond to orientation transformations in the image plane, as *b* vs. *q*, but not to mirror-image contrasts, as *b* vs. *d*.

At the brain level, previous studies have shown increased activation in the left occipitotemporal sulcus in response to visual words and legal sequences of letters compared to control visual stimuli, throughout literacy acquisition (Ben-Shachar, Dougherty, Deutsch, & Wandell, 2011; Dehaene, Pegado, et al., 2010). Specifically, McCandliss, Cohen, and Dehaene (2003) review the evidence for an area located at the *left ventral occipitotemporal cortex* (henceforth, LvOT) adjacent to the fusiform gyrus, named the *Visual Word Form Area* (VWFA). This brain region has shown to develop specific activation to visual word-related stimuli versus controlled visual stimuli in literate adults (Cohen et al., 2002; McCandliss et al., 2003). Using a different method, prior to the discovery of the VWFA, the work of Dejerine (1892) already indicated the existence of a cortical region dedicated to reading, with his report of a patient with *pure alexia* (i.e., inability to read, but preserved letter recognition, in the absence of any other cognitive disorder), following a lesion in the left inferior occipitotemporal cortex, while preserving his writing and other cognitive abilities, including visual ones. Furthermore, using *functional magnetic resonance imaging* (fMRI), Cohen et al. (2002) demonstrated that literate adults show stronger activation in the VWFA in response to visual words, compared to unpronounceable strings of consonants or images of checkerboards, suggesting that the VWFA becomes tuned to language-dependent parameters and orthographic rules such as letter combination. Converging evidence has demonstrated that the emergence of a region tuned to the orthographic code in literate participants presents a consistent location irrespective of writing system (i.e., alphabetic, syllabic or morpho-syllabic; Bolger, Perfetti, & Schneider, 2005), culture (e.g., in Japanese and in French participants; Dehaene, Nakamura, et al., 2010) or age at which one learns to read (i.e., similar pattern of cortical specialization for *late-literate* adults, who learned to read in special alphabetization classes during adulthood, and for *early literate* adults, who learned to read during childhood, in regular schooling; Dehaene, Pegado, et al., 2010).

The discovery of a specialized cortical region for orthographic material has raised the question of whether such a recent cultural invention as writing (< 5400 years ago) could have carried out the evolution of an inbuilt mechanism dedicated to reading (McCandliss et al., 2003). Indeed, the invention of writing is too recent to have possibly altered the human genome through selective pressure (Dehaene, 2004). Therefore, Dehaene (2004) proposes that during literacy acquisition pre-existing neural systems (with similar function to those required by cultural inventions and sufficiently plastic to allow partial reorganization for a novel use), are “recycled” to accommodate to a different purpose than their original one. Similarly to the concept of *exaptation* by Gould and Vrba (1982), Dehaene’s *neuronal recycling hypothesis*, proposes that selective pressure throughout human evolution resulted in the emergence of specific innate functions (e.g., language), yet the brain does not fully constrain to them. Brain plasticity and training enable these structures to be co-opted for more recent cultural inventions, such as literacy and arithmetic (Dehaene, 2004; Dehaene & Cohen, 2007, 2011). According to the *neuronal recycling hypothesis*, the recruitment and adaptation of original functions of the brain to accommodate recent cultural advances, in an optimal functioning way, may result in spillover effects (Dehaene & Cohen, 2007). Indeed, previous studies have shown that by relying on pre-existing neuronal resources, the acquisition of literacy impacts in evolutionary-older functions, such as visual recognition of objects and faces (e.g., Kolinsky & Fernandes, 2014; Ventura, 2014).

Given that literacy is underpinned by a brain region whose function (rooted by evolution) originally supports visual object recognition (i.e., the LvOT, which is part of the ventral visual stream; Milner & Goodale, 2008), it possesses original properties deemed advantageous towards reading (Cohen et al., 2002; Logothetis et al., 1995). Namely, it is invariant to object size and position (e.g., “h” and “h” represent the same letter), and it discriminates minor variations in form (e.g., “e” and “c” represent different letters). It is also able to learn arbitrary associations that are independent of visual features, and hence, it is capable of ignoring major form variations (e.g., the different allographs “ 𝒥 ”, “J” and “j” all map onto the same abstract letter representation). This categorization, supported by the LvOT, also facilitates grapheme to phoneme associations, given that one can learn unrelated visual to auditory relationships (i.e., the ability to associate the visual symbol or grapheme to its correspondent phoneme in the case of alphabetic scripts; Hoffman & Logothetis, 2009). Moreover, as aforementioned, the ventral visual stream is originally sensitive to orientation contrasts in the picture plane (Logothetis et al., 1995; Rollenhagen & Olson, 2000). However, it is not originally sensitive to all orientation contrasts. In fact, one original property of the visual system that might be deleterious when learning to read is mirror invariance, given that lateral reflected images are processed as the same percept (e.g.,  and  generate a common visual representation) but some scripts comprise *reversible* letters (i.e., letters that differ from others solely by orientation and consist of the same visual shape and features), including mirror images as the pairs of letters *d* and *b* or *q* and *p* in the Latin Alphabet. Therefore, during literacy acquisition, one must develop strategies to unlearn or at least to suppress mirror invariance for successful reading (Perea, Moret-Tatay, & Panadero, 2011).

In accordance with the neuronal recycling hypothesis, previous studies demonstrate that the ability to discriminate mirror images (i.e., *enantiomorphy*), acquired during literacy acquisition, impacts in non-linguistic visual object recognition (Casey, 1984; Dehaene, Pegado, et al., 2010; Pegado, Nakamura, Braga, et al., 2014). Moreover, mirror discrimination emerges only when the script itself contains mirrored symbols. Indeed, fluent readers of scripts that do not contain mirrored letters, such as Tamil readers, continue to show mirror invariance, presenting difficulties in discriminating lateral reflections (Danziger & Pederson, 1998). The effects of enantiomorphy in visual perception for non-linguistic material are not due to general factors as schooling or formal instruction, but rather specific to literacy acquisition in a script with mirrored symbols, given that late-literate adults show an advantage in mirror-image discrimination of non-linguistic material when compared to illiterate adults (controlled for formal instruction variables; e.g., attendance in school), excluding the possibility that mirror discrimination effects in object recognition were the result of neural maturation (Kolinsky et al., 2011).

Despite the converging evidence from the reviewed literature on the impact of literacy in visual perception, its contribution towards the development and predictions made by contemporary computational models of visual word recognition is still scarce. In other words, to the best of our knowledge, no model to date has examined the computations involved in mirror-image discrimination in the course of orthographic processing (for a similar argument see Perea, Moret-Tatay, & Panadero, 2011). Furthermore, it is unclear whether mirror-image discrimination, as an additional mechanism, is indeed a relevant property during orthographic processing, or whether, as put by Dehaene, Nakamura, et al. (2010), as long as literacy has already been acquired, mirror-discrimination happens automatically, early on, even before specialized processing by the reading system.

The first and most influential computational model of visual word recognition, i.e., the *interactive-activation model* (henceforth, IAM; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982) has led to the development of other models, such as the Spatial Coding Model (Davis, 2010) and the multinomial interactive activation model (McClelland, 2013; Mcclelland, Mirman, Bolger, & Khaitan, 2014). In its earliest form, the IAM assumes a localist representation (illustrated in Figure 1): it comprises three levels of processing in a network of *nodes* (abstract units of representation) that correspond to features, letters, and words. The IAM posits that word recognition involves parallel processing, with simultaneous activity between nodes occurring within the three levels of representation. It also assumes that top-down and bottom-up interactions occur between these levels. So, besides the parallel connections that take place within levels (with inhibitory connections within some of the levels), inhibitory and excitatory connections may also occur between word, letter and feature levels (with feature and word levels not being directly connected; McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Ultimately, the constraints derived from the interaction of nodes, in response to a certain input, lead to an optimal level of activation for a specific word node, allowing word recognition.

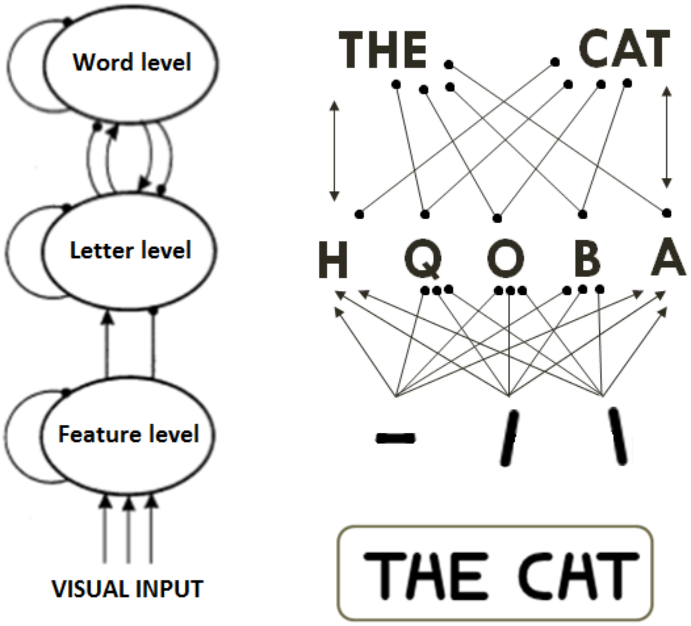

Figure 1: Interactive activation model

Representation of the IAM (left; Rumelhart & McClelland, 1982) and example of the model’s interactions between levels during perception of two words (right). Arrows and dots denote excitatory and inhibitory interactions, respectively. For simplicity, the inhibitory connections within levels are not represented in the example.

For clarity, take the example in Figure 1. In the presented expression “the cat” (the critical letters are underlined), despite the letters *H* and *A* taking the same form in the input, a skilled reader has no problem in differentiating them. According to the IAM, during the early stages of word processing, both nodes for the letter *H* and *A* are activated, due to the presence of (ambiguous) features in the input that can map into both *H* and *A* letter representations. However, top-down feedback from the word level will inhibit the letter nodes that do not correspond with the word node active at that moment. Thus, the node for the word “THE” will inhibit the node for the letter “A” and the node for “CAT” will inhibit the node for “H”, solving the ambiguity. It is important to note that ambiguity, in this case, exists since within-level connections are always inhibitory. Therefore, the activation of a letter node will inhibit all other letter nodes, meaning that during the perception of both words given in the example, the letters “H” and “A” compete for recognition.

Contrasting with the interactive-activation (IA) approach, other models assume that reading functions as an optimal *Bayesian* decision-making process. Two examples are the *Bayesian Reader* (Norris, 2006) and the *noisy-channel model* (Norris & Kinoshita, 2012; Norris, Kinoshita, & van Casteren, 2010). These models assume that visual word perception operates under a *noisy channel* (the visual system), that distorts visual inputs, introducing uncertainty towards the recognition of words, the letters that compose them, letter position, and even their presence or absence (Norris & Kinoshita, 2012). According to the noisy-channel, and following Bayes’ theorem, a word is recognized when its likelihood (probability) to generate the noisy output (i.e., the perceived sample of an input) reaches a certain threshold. For each word within a reader’s lexicon, the model computes the likelihood of an input (specific word) being present, based on accumulated evidence from the noisy channel (i.e., the generated output sample) and previous knowledge (e.g., word frequency; Norris & Kinoshita, 2012). Using the example in Figure 1, the middle position letter in both words introduces uncertainty towards letter, and consequently word identification. However, for both cases, the words with a higher probability of generating the noisy outputs (or samples) “” and “” are the respective words “THE” and “CAT”, given that there are no letters with similar features to those perceived, other than *H* and *A*, that can be substituted in those positions to generate a word present in the lexicon.

Both approaches (i.e., IA and Bayesian models) have been reformulated in newer accounts to better fit and simulate data. However, the revision of specific parameters in these models has been mainly focused in word variables such as length and frequency (e.g., Spatial Coding Model; Davis, 2010). For example, in the case of IA based models, the use of a fixed uppercase letter coding scheme for computation has limited the possibility of predictions regarding orientation contrasts in lowercase-letter identification, or visual similarity effects in word recognition (e.g., Marcet & Perea, 2017; Perea, Moret-Tatay, & Panadero, 2011). Also, despite not assuming a fixed coding scheme for features, Bayesian models predict that different transformations in letter orientation, introduce the same level of uncertainty towards recognition, since they share the same features and overall visual shape (e.g., “ibea” and “ipea” introduce the same level of uncertainty/noise towards the identification of the word “idea”, having the same probability of activating it).

Taking into account that mirror-image generalization is rooted in evolution, Carreiras, Perea, and colleagues (e.g., Duñabeitia et al., 2011; Perea, Moret-Tatay, & Panadero, 2011) have suggested that throughout literacy acquisition this property of the visual system is never entirely erased, and that it might persist during early stages of orthographic processing by fluent readers. Considering the within letter level inhibitory connections postulated by the IAM, Perea, Moret-Tatay, and Panadero (2011) hypothesized that only *reversible* letters (i.e., for which orientation is a diagnostic feature; e.g., *d*, *p*, *b*; *N*, *Z*) are affected by the suppression of mirror generalization. It is only for these letters that a lateral reflection transformation generates an existing and different grapheme (e.g., d and b). In contrast, for *nonreversible* letter (i.e., which differ from other letters of the script by visual shape and features, and hence, for which orientation is not a diagnostic feature; e.g., r or f), the lateral reflection still activates the corresponding letter node, instead of inhibiting it, because mirror-generalization would still operate and the additional step of mirror suppression would not be necessary in the course of orthographic processing.

To test these predictions, Perea, Moret-Tatay and Panadero (2011) used a masked priming paradigm with a lexical decision task, where they compared recognition of target words, comprising a critical letter that was either reversible (e.g., IDEA) or nonreversible (e.g., ARENA), and were primed by the *identical* letter, in lower case (e.g., idea; arena), by a *mirrored* letter (e.g., ibea; aɿena), or by an unrelated, *control* letter (e.g., ilea; acena). These authors demonstrated that despite perceptual similarity between pairs of reversible letters (d/b and q/p), the substitution of these letters by their mirrored version interfered with word recognition (e.g., the prime "danana" resulted in significantly slower recognition of the target "BANANA", when compared with the substituted letter control prime "tanana"; Perea, Moret-Tatay, & Panadero, 2011; Experiment 1). This interference, however, did not occur for nonreversible mirrored letters. Moreover, when using a better-controlled prime condition (i.e., the critical letter in the prime was substituted by a nine-dot pattern - e.g., "i▒ea" for the target IDEA), on which possible confounds from activation of other letters in the critical-letter position were severely reduced, still the mirrored version of reversible and of non-reversible letters produced opposing priming effects in word recognition. The mirrored version of reversible letters led to inhibitory priming effects (e.g., prime "ibea" produced slower response times to the target "IDEA" relative to the control prime), whereas the mirrored version of non-reversible letters led to facilitatory priming effects (e.g., prime “ aɿena” produced a faster response to the target “ARENA”, relative to the control prime - Perea, Moret-Tatay, & Panadero, 2011; Experiment 3). This pattern of results argues in favor of the proposal that mirror generalization still happens early on during orthographic processing, with mirror-image suppression being restricted to reversible letters.

Nonetheless, an alternative explanation based on IA’s assumptions, regarding lateral inhibition between letter nodes at the letter level (McClelland & Rumelhart, 1981), could account for the results reported by Perea, Moret-Tatay, and Panadero (2011). We thus hypothesize that during early stages of orthographic processing, the orientation transformation of any letter (reversible or nonreversible), will activate the node of letters that share the most features and overall visual shape with the presented input. Therefore, any orientation transformation of nonreversible letters would be mostly compatible with only one abstract letter, and hence, map onto the abstract representation of the real letter (e.g., the inputs “aɿena” and “aɹena” would lead to the activation of the grapheme <r>, and in turn, to activation of the word <ARENA>), whereas orientation transformations of reversible letters would activate multiple letter representations, that is, all representations that are compatible with the visual input, in terms of features and visual shape. In this latter case, for the target IDEA (critical letter: D) the orientation transformation (either mirrored or plane-rotated version: e.g., b and p, respectively) would activate the three letter representations that are compatible with the input (that is, b, p, and d), resulting in competition effects due to the inhibitory links between abstract letter identity nodes (e.g., the inputs “ibea” and “ipea” would activate the letters *b* and *p*, respectively, but also to some significant extent the other letters with the same features and shape, that is, *d* and *q*. Thus, all abstract letters compatible with the input would compete through lateral inhibitory connections. Given that the mirrored and rotated versions (that is <b> and <p>) would compete for recognition with the target grapheme <d>, in our example, both "ibea" and "ipea" would lead to a reduced activation for the word "IDEA" relative to a control prime. Thus, the effects reported by Perea, Moret-Tatay and Panadero (2011) regarding mirror invariance suppression, could instead be accounted by feature sharing between the input and abstract letter representations, rather than due to a mechanism of mirror-image suppression. This proposal would explain the pattern of results found previously for identical and mirrored primes of reversible and nonreversible letters.

To disentangle and to test the two accounts (i.e., whether mirror-image generalization is not part of orthographic processing: e.g., Dehaene, Pegado, et al., 2010; Pegado, Nakamura, & Hannagan, 2014; vs. mirror-generalization is specifically suppressed when necessary during orthographic processing: e.g., Duñabeitia et al., 2011; Perea, Moret-Tatay, & Panadero, 2011), in the two experiments of the present work, we adopted a design similar to that of Perea, Moret-Tatay and Panadero (2011; Experiment 3), examining reversible (b, d, and p) and nonreversible letters (f, r, t). We also ensured in a pretest that sets controlled for the number of visual features; cross-case visual similarity, and also in psycholinguistic variables known to affect word processing (see Chapter 2; Method). In both experiments of the present study, the difference from the original work was in the inclusion of the rotated prime condition, the priming paradigm (in Experiment 1) and the task itself (in Experiment 2).

First, given our hypothesis that a mechanism of mirror invariance would not fully account for the pattern of results in Perea, Moret-Tatay, and Panadero (2011; Experiment 3), we added the *rotated* prime condition, in which the critical letter was a 180º plane rotation of the critical letter (e.g., ipea; critical letter underlined), to the three prime-target conditions adopted by these authors (i.e., control, nine-dot pattern; identical; and mirrored). The 180º plane rotation differs from the target letter by the same angular difference than the mirror image, but discrimination of plane rotations is an original property of the ventral occipitotemporal cortex that does not depend on literacy acquisition. Indeed, both illiterate adults and preliterate children are quite able to discriminate plane rotations, whereas they exhibit a specific difficulty in the discrimination of mirrored images (e.g., Fernandes & Kolinsky, 2013; Fernandes et al., 2016; Kolinsky et al., 2011). In other words, in the present work, we explored whether plane-rotations of the critical letters (i.e., their *rotated* version) would lead to similar patterns of priming in visual word recognition as the mirrored version.

Second, in Experiment 1, we adopted a *sandwich priming* paradigm with lexical decision (cf. Lupker & Davis, 2009). In this paradigm, before each prime and after the forward mask, a lower-case version of the target is presented for ~33ms, activating target words prior to the presentation of the primes. This change allows reducing possible confounds that classic masked priming and form-priming paradigms might entail due to lexical inhibition effects (Norris & Kinoshita, 2008). Specifically, differences in prime conditions where a letter is substituted by another when altering its orientation (which happens in the case of reversible letters) may be due to elicited activation of different competitors at the word level, equivalent to the number of neighbors a prime has (e.g., the primes “ibea” and “ipea” could elicit different competitors).

In Experiment 1, we adopted the sandwich masked priming paradigm with lexical decision in a 2 (Lexicality: word; non-word) x 2 (Letter type: reversible; nonreversible) x 4 (Prime-target relation: control, identical, mirrored; rotated) design.

For nonreversible letters, since no letter nodes are compatible with the transformed letter’s features (other than the base letter), we expected identical and orientation-transformations of the critical letter to facilitate the recognition of the target word (e.g., identical (arena), mirrored (aɿena

) and rotated (aɹena) primes should lead to faster response times for the target “ARENA”, relative to control the prime “a▒ena”). However, orientation transformation primes (i.e., mirrored and rotated) were expected to produce less facilitation towards target recognition relative to identical primes (i.e., faster decision times for targets primed by the identical letter relative to mirrored and rotated letters). Indeed, despite nonreversible letters transformed in orientation not mapping onto different abstract representations, the orientation transformation of nonreversible letters should still introduce some level of noise towards its recognition, and particularly if the discrimination of orientation (either mirrored or rotated) occurs automatically and early on during orthographic processing as we hypothesize.

For reversible letters, we expected both orientation contrasts to inhibit the recognition of the target word (i.e., mirrored (ibea) and rotated (ipea) primes should lead to slower response times for the target “IDEA”, relative to the control “i▒ea”). Since orientation contrasts of reversible letters map on to different abstract representations, mirrored and rotated primes would activate letter nodes incompatible with the target word, interfering in its recognition.

During masked priming, as used in this task, prime and target are treated as a single perceptual unit, and by presenting a pseudoword in the prime (which happens when a reversible letter is transformed in orientation) the target might be confused by a pseudoword, hence the inhibitory effects for orientation contrasts (Norris & Kinoshita, 2008, 2012). This, in turn, should not occur for identical primes of reversible letters, for which priming should be facilitatory (i.e., faster target response for identical primes, relative to control primes) since the connection between the letter node activated and the target word node is facilitatory. In this case, both prime and target increase the likelihood (probability) of the target being perceived as a word.

In Experiment 2, to further control for lexical interferences in letter recognition, and hence, to ensure that the pattern of priming effects of Experiment 1 would not be due to top-down lexical effects, instead of early orthographic processes, a *same-different* task with masked priming was adopted (cf. Norris & Kinoshita, 2008), using the same letter sets (i.e., reversible and non-reversible) and prime conditions of Experiment 1 (i.e., control, nine-dot pattern; identical; mirrored; rotated). In Experiment 2, participants had to decide whether target words were the same or different than previously presented reference words, regardless of the letter case. Priming effects in this task should depend on perceptual similarity between prime and target, since participants' decision does not depend on lexical activation, which happens in the case of a lexical decision task (i.e., word vs non-word decision), introducing possible confounds in letter recognition due to word and letter level interactions (McClelland & Rumelhart, 1981; Norris & Kinoshita, 2008). Therefore, Experiment 2 allowed us to test whether priming effects in Experiment 1 occurred due to low-level perceptual differences at the feature and letter levels, or due to higher level influences, such as lexical competition between different prime conditions and target. With Experiment 2, we hoped to obtain converging evidence towards the hypothesis that orientation discrimination (mirrored and rotated) occurs early on during orthographic processing, regardless of letter type (reversible or nonreversible) and before lexical access. If this is true, the pattern of results for Experiment 2 should be similar to the expected effects mentioned for Experiment 1.

2. Experiment 1

2.1. Method

2.1.1. Participants

Thirty-six undergraduate students from Universidade de Lisboa (7 males, M_{age} 21.5, SD = 5.4) took part in this experiment in exchange for a course credit. All participants were right-handed, had no history of developmental, neurological or psychiatric disorders, had a normal or corrected-to-normal vision and were native speakers of Portuguese. Informed consent was obtained orally, before the experimental session. Two women were excluded due to low performance in nonword trials (average accuracy of 43%).

This study was approved by the Deontological Committee of Faculdade de Psicologia, Universidade de Lisboa.

2.1.2. Design

In this experiment, we used a lexical decision task, in a 2 Lexicality (word vs. non-word) x 2 Letter type (reversible vs. nonreversible) x 4 Prime condition (control; identical; mirrored; rotated) design. This experiment extends Perea et al. (2011; Experiment 3), with the addition of the rotated prime condition, and the use of the sandwich priming paradigm (Lupker & Davis, 2009). For dependent variables, response latency and accuracy rates were measured.

2.1.3. Materials

Two sets of 192 of Portuguese words, 4-9 letters long, with 2-4- syllables were selected. The critical letter of the items was *b*, *d*, or *p* for the reversible-letter set, and *f*, *r*, or *t* for the nonreversible-letter set. The lowercase-uppercase pair of the two sets did not differ in cross-case visual similarity (Boles & Clifford, 1989), $t < 1$. The letter *q* was not included in the reversible letter set because in Portuguese it is always part of the complex grapheme <qu>.

Position of the critical letter did not differ between sets, $t(382) = 0.35$, $p = 0.73$. Sets were also matched in word frequency, $t(382) = - 0.60$, $p = 0.55$ (based on Corlex Portuguese database), orthographic neighborhood density, $t(382) = - 0.17$, $p = 0.86$, phonological neighborhood density, $t(382) = - 0.40$, $p = 0.69$, and number of phonological and orthographic neighbors that differed from the target by the critical letter, $t(382) = -0.17$, $p = 0.87$. Descriptive statistics and items used in the word sets are presented in the Appendix.

For the lexical decision task, two sets of 192 legal nonwords, 4-9 letters long, and with 2-4 syllables were created by replacing letters from Portuguese words. The same critical letters, *b, d* or *p* for reversible-letters and *f, r* or *t* for nonreversible-letters were used. Identically to words, the position of the critical letter in nonwords did not differ between reversible and nonreversible sets, $t\,(382) = 0.47$, $p = 0.64$. Item cross-case similarity was also equated between sets (Boles & Clifford, 1989), $t < 1$.

An uppercase version of every item was created (e.g., "CAUDA" - tail; "GERAL" – general; critical letter underlined) to be used as a target, and four lowercase versions to be used as the masked priming. As mentioned in the Introduction (section 1), the primes comprised an *identical* condition (i.e.,, prime and target differed only in case – "cauda"; "geral"), a *mirrored* condition (i.e., critical letter in prime replaced by its lateral reflected image – "cauba"; "geɿal"), a *rotated* condition (i.e., critical letter in prime replaced by its 180º rotation on the image plane – " caupa"; "geɹal") and a *control* condition (i.e., critical letter in prime replaced by a mask – "cau▒a"; "ge▒al"). The *control* primes allowed to assess the magnitude of priming relative only to the critical letter, when compared with the other primes (i.e., identical, mirrored and rotated).

2.1.3.2. Pretest: 2AFC *Identification task*

The critical letters used and their orientation contrasts (i.e., mirrored and rotated) were pre-tested to ensure that they were perceived as similar between them as with the critical letter, so that we could exclude the possibility that in the main experiment any difference between the priming effects for rotated and mirrored primes was not merely the result of low-level perceptual differences between critical letters and their orientation transformations. For this purpose, we adopted a two-alternative forced-choice identification task similar to the one of Kinoshita, Robidoux, Mills, and Norris (2014). Twenty fresh undergraduate students from Universidade de Lisboa (3 males, M_{age} 18.5; SD = 0.60) participated in exchange for a course credit. Each trial started with a forward mask comprising a 3-cardinal string (###) presented in the center of the screen for 500 ms, followed by the target. The target was a single stimulus: either a lowercase version of the critical letters of the main experiment or the modified version of that critical letter (i.e., mirrored, rotated and control: nine-dot pattern) flanked by % signs (e.g., "%d%"). It was presented for 48 ms (3 refresh cycles), and immediately followed by a backward mask, composed of # and @ signs overlaid on each other. The two alternatives (i.e., target and distractor) were presented to the left and right side of the backward mask until participant response (by pressing the left or right key accordingly) or until 10 s had elapsed. The critical letters (b, d, p; f, r, t) and their modified versions (mirrored, rotated and control) were presented equally often as target and as distractor to exclude response bias due to letter familiarity; the correct alternative was presented equally often on the right and left side of the backward mask.

Accuracy rates were analyzed with an ANOVA on the 3 target types [1](mirrored; rotated; control) x 2 letter type (reversible; nonreversible) design. Only the main effect of target type was significant, $F_1(2, 38) = 45.31$, $p < .001$, $\eta p^2 = .70$, $MSE \sim 0.03$. Participants found it easier to discriminate the nine-dot pattern from distractors, relative to other targets (mirrored and rotated letters), with 86.3% correct choices for reversible letter distractors and 85.05% for nonreversible. Critically, participants found as hard to discriminate the target when it was a mirrored version of the distractor, for both reversible (M= 54.65%) and nonreversible letters (M= 53.35%), as well as when it was a rotated version of the distractor, for both reversible (M= 54.10%) and nonreversible letters (M= 49.15%). Thus, critical letters and their modified versions were equated in their low-level perceptual confusability (e.g., *b*, *d* and *p* share the same level of similarity between them), excluding this artifact as a possible explanation to priming effects in the experiment.

2.1.4. Apparatus and Procedure

Participants were tested in a quiet, dimly lit room in groups of two to six. Presentation of stimuli and data collection were controlled by E-Prime 2.0 in Windows XP. Participants sat at an approximate distance of 60 cm from the monitor (CRT; 17’’; resolution: 1024 x 768 pixels; refresh rate of 60 Hz; 16.67 ms refresh cycle).

The sequence of events consisted on the presentation of a forward mask comprising 9 cardinals (#########) for 500 ms, immediately followed by a lower-case version of the target item for ~33 ms (2 refresh cycles) (cf. Lupker & Davis, 2009). The prime was then presented for ~48 ms (3 refresh cycles), and followed by the target, that remained on the screen until participant’s response or until 2500 ms had elapsed if no response was given. All stimuli were presented in the

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[1] In relation to the distractor (i.e., target could be one of three possible modified versions of the critical letter distractor)

same location of the forward mask, covering over and beyond all primes. The inter-trial interval was 450 ms (blank screen). Timing and sequence of events for each trial is presented in Figure 2.

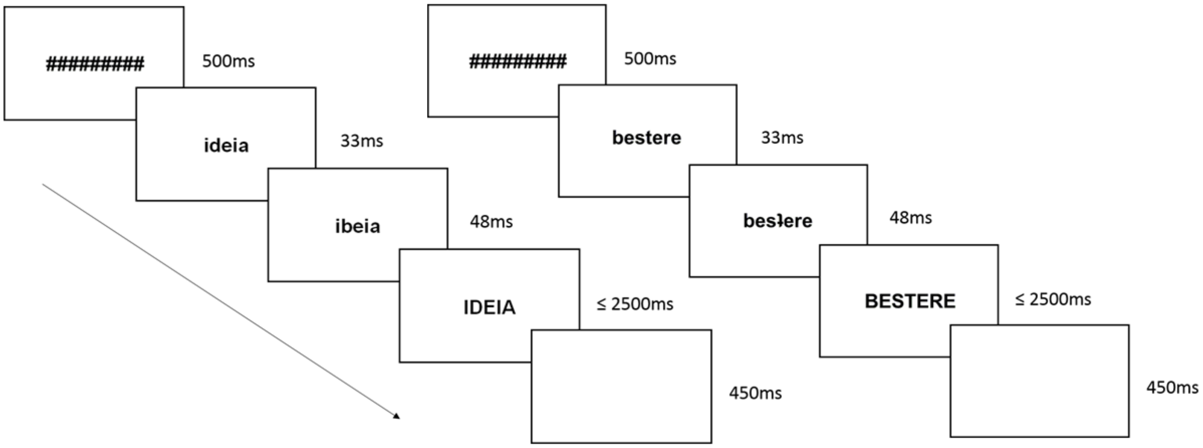

Figure 2: Procedure used in the sandwich priming with lexical decision task.

Illustration of sequence of events for each trial. Example of a trial for a word item and reversible letter in mirrored prime condition (left); and Nonword item and non-reversible letter in rotated prime condition

Participants were informed about the appearance of a forward mask, and asked to decide whether the target (the uppercase letter-string) was a Portuguese word or a not, as fast and as accurately as possible, by pressing the number keys “5” (for yes) or “1” (for no) with the right and the left index finger, respectively. The presence of primes was not mentioned, and to make sure participants understood the task, they performed a 16-trial practice list with feedback on accuracy and response times.

Four experimental lists were created to counterbalance the four prime conditions, using a Latin square, ensuring no repetition of items for each participant and that all items occurred in all prime conditions across participants (each participant was presented with 48 items in each condition of Lexicality x Letter x Prime-target relation). The order of trials was randomized in two blocks separated by a self-paced break in-between.

2.2. Results and Discussion

Reaction times (RTs) for correct decisions were trimmed (2.5 *SD* above and below the grand mean RT for each participant, plus exclusion of RT lower than 200 ms; data excluded: 2.65%). Accuracy (proportion of correct responses) was analyzed separately (see Table 1).

Table 1 Participants mean response times (in ms) and percent correct responses (in parentheses) for word and nonword targets in Experiment 1.

	Prime Condition			
	Control	Identical	Mirrored	Rotated
Words				
Reversible letters	530 (93.8)	491 (95.7)	541 (91.0)	552 (89.7)
Nonreversible letters	542 (92.5)	496 (96.1)	511 (94.5)	531 (91.3)
Nonwords				
Reversible letters	592 (92.3)	578 (89.0)	574 (92.2)	583 (92.8)
Nonreversible letters	586 (93.7)	573 (92.9)	580 (91.4)	573 (93.0)

Nonword items were excluded from the analyses reported, given that robust priming effects are usually found in the lexical decision for word targets only, and not for nonwords (Kinoshita & Norris, 2009, 2012), even in the sandwich priming paradigm (Lupker & Davis, 2009).

Repeated measures 2 Letter type (reversible vs nonreversible) x 4 Prime-target condition (control; identical; mirror; rotation) ANOVAs were conducted separately on mean accuracy rates and on RTs for correct decisions (after trimming). To ensure normalization of data distribution, accuracy was arcsine transformed and RTs were logarithmized. Results are reported for participants (*F*1) and for items (*F2)* as the random factor; effect sizes correspond to partial eta squared ηp^2 for the omnibus effects and Cohen d_z for pairwise contrasts.

RTs for correct word decisions

The ANOVA on RTs showed a significant interaction between letter type and prime condition, $F_1(3, 99) = 17.51$, $p < .001$, $\eta p^2 = .35$, $MSE \sim 0.00$ ($F_2(3, 1146) = 20.00$, $p < .001$ $\eta p^2 = .05$, $MSE = 0.01$), a main effect of letter type, $F_1(1, 33) = 18.07$, $p < .001$, $\eta p^2 = .35$, $MSE \sim 0.00$ ($F_2(1, 382) = 7.00$, $p = .006$, $\eta p^2 = .02$, $MSE = 0.02$), and prime condition, $F_1(3, 99) = 94.95$, $p < .001$, $\eta p^2 = .74$, $MSE \sim 0.00$ ($F_2(3, 1146) = 77.00$, $p < .001$, $\eta p^2 = .17$, $MSE \sim 0.01$).

The identical priming effect was significant and was not modulated by letter type. Participants were significantly faster on word decisions for the identical prime condition, when compared with the control prime condition, $F_1(1, 33) = 189.71$, $p < .001$, $\eta p^2 = .85$ ($F_2(1, 382) = 149$, $p < .001$, $\eta p^2 = .28$), with no interaction of letter-type, $F_1(1, 33) = 1.04$, $p = .32$, $\eta p^2 = .03$ (F_2 $(1, 382) = 0.0$, $p = .59$, $\eta p^2 \sim .00$).

In contrast, as demonstrated in Figure 3, the priming effect of orientation transformation (mirrored and rotated) was modulated by letter type. As predicted, mirrored primes produced slower word decisions for reversible letters, and faster word decisions for non-reversible letters, compared to control primes $F_1(1, 33) = 40.63$, $p < .001$, $\eta p^2 = .55$ ($F_2(1, 382) = 36$, $p < .001$, $\eta p^2 = .087$). This interaction also occurred for rotated primes, with an inhibitory priming effect for reversible letters and facilitatory for nonreversible letters $F_1(1, 33) = 30.11$, $p < .001$, $\eta p^2 = .07$ ($F_2(1, 382) = 29$, $p < .001$, $\eta p^2 = .07$.

Moreover, despite critical letters and their orientation transformations being equated in their confusability (see Method), response times for mirrored and rotated prime conditions differed; rotated primes lead to significantly slower word decisions than mirrored primes, $F(1, 33) = 18.29$, $p <.001$, $\eta p^2 = .36$ ($F_2(1, 382) = 20$, $p < .001$, $\eta p^2 = .05$). Thus, these results suggest that the level of uncertainty towards letter recognition during word recognition is influenced by the input's orientation. Indeed, rotated letters in the picture plane (e.g., d and p; r and ɹ) are originally easier to discriminate by the LvOT, consequently introducing more noise to the visual decoding system (Norris & Kinoshita, 2012), than lateral reflected letters (e.g., d and b; r and ɿ). This effect was not modulated by letter type, F (1, 33) = 2.34, p = .14, $\eta p^2 = .07$ ($F_2(1, 382) = 2$, p = .18, ηp^2 ~ .00), suggesting that the discrimination of orientation contrasts during visual word recognition affects reversible and non-reversible letters similarly.

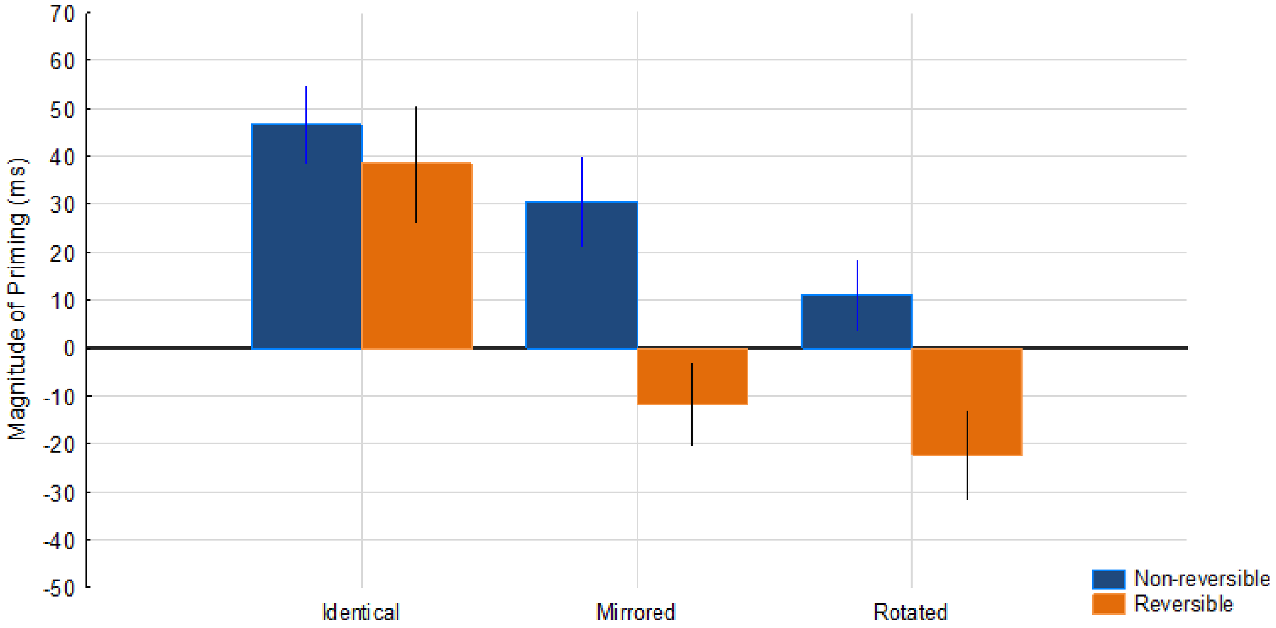

Figure 3: Illustration of priming effects obtained in Experiment 1.

Magnitude of priming and SEM for correct responses to target words in the non-reversible letter type set (blue) and reversible letter type set (orange). Magnitude of priming corresponds to the RT difference between prime type (identical; mirrored and rotated) and the control prime condition.

In line with our hypothesis, for reversible letters, there was an inhibitory priming effect when mirrored and rotated versions of the letter were presented, as demonstrated in Figure 3. As expected, relative to control primes, participants were significantly slower when the target was primed by a mirrored version of the critical letter, $t_1(33) = -2.94$, $d_z = 0.51$, $p < .01$ ($t_2(191) = -2.73$, $p = .007$) or by a rotated version, $t_1(33) = -4.68$, $d_z = 0.82$, $p < .001$ ($t_2(191) = -5.37$, $p < .001$).

For nonreversible letters, a facilitatory priming effect was found; hence participants were faster when the target was preceded by either a mirrored or rotated prime compared to control primes, $t_1(33) = 7.05$, $d_z = 1.22$, $p < .001$ ($t_2(191) = 5.75$, $p < .001$) and $t_1(33) = 2.85$, $d_z = 0.49$, $p = .008$ ($t_2(191) = 2.25$, $p = .025$), respectively. Notably, as predicted, the magnitude of priming (i.e., RT difference relative to control primes) differed between identical and orientation transformed primes (i.e., mirrored and rotated) in nonreversible letters. Target response was slower when mirrored and rotated primes were presented, compared to identical primes, $t_1(33) = -3.84$, $d_z = 0.67$, $p < .001$ ($t_2(191) = -2.63$, $p = .009$) and $t_1(33) = -7.42$, $d_z = 1.29$, $p < .001$ ($t_2(191) = -6.42$, $p < .001$), respectively. Thus, participants were sensitive to both orientation contrasts, even when orientation was not advantageous for letter identification. Sensitivity towards a transformation in letter orientation that relies on an original property of the visual system (plane rotation discrimination; Logothetis et al., 1995) suggests that a mechanism of mirror invariance suppression, as proposed by Perea, Moret-Tatay and Panadero (2011), may not fully explain the inhibitory and facilitatory effects observed for reversible and nonreversible mirrored letters, respectively. In turn, mirror discrimination seems to occur automatically during early stages of orthographic processing, and the IA's account for inhibitory connections between letter nodes of reversible letters (which does not occur between nonreversible letters and their orientation transformed versions) is able to account for the reported effects.

Accuracy

The analysis on accuracy was consistent with the one run on RTs. We also found a significant interaction between letter type and prime condition, $F_1(3, 99) = 7.02$, $p < .001$, $\eta p^2 = .18$, $MSE \sim 0.01$, $F_2(3, 1146) = 3.22$, $p = .022$, $\eta p^2 = .008$, $MSE \sim 0.04$, and a significant main effect of letter type, $F_1(1, 33) = 5.06$, $p = .031$, $\eta p^2 = .13$, $MSE \sim 0.01$ ($F_2(1, 382) = 2.65$, $p = .10$, $\eta p^2 = .007$, $MSE = .058$), and prime condition, $F_1(3, 99) = 22.28$, $p < .001$, $\eta p^2 = .40$, $MSE \sim 0.01$ ($F_2(3, 1146) = 19.76$, $p < .001$, $\eta p^2 = .049$, $MSE \sim 0.039$). Participants were more accurate on word decisions for the identical prime condition, relative to primes in the control condition, $F_1(1, 33) = 25.41$, $p < .001$, $\eta p^2 = .44$ ($F_2(1, 382) = 149$, $p < .001$, $\eta p^2 = .28$), which was not affected by letter type, $F_1(1, 33) = 1.52$, $p = .23$, $\eta p^2 = .044$ ($F_2 = 0.00$, $p = .58$, $\eta p^2 = 0.0$). The mirrored priming effect was not significant, $F_1(1, 33) = 0.03$, $p = .87$, $\eta p^2 = 0.0$ ($F_2(1, 382) = 5$, $p =.026$, $\eta p^2 = .013$), but it was affected by letter type. Mirrored priming produced an inhibitory effect for reversible letters, with less accurate target responses, and facilitatory effect for nonreversible letters, with more accurate responses, $F_1(1, 33) = 19.35$, $p < .001$, $\eta p^2 = .37$ ($F_2(1, 382) = 36$, $p < .001$, $\eta p^2 =. 087$). In turn, relative to controls, rotated primes where not modulated by letter type, $F_1(1, 33) = 3.79$, $p = .06$, $\eta p^2 = .10$ ($F_2(1, 382) = 29$, $p < .001$, $\eta p^2 = .071$), but produced a global inhibitory effect, $F_1(1, 33) = 8.13$, $p = .007$, $\eta p^2 = .19$ ($F_2(1, 382) = 5$, $p = .023$, $\eta p^2 = .013$), with less accurate participants' response to rotated primes, relative to controls. As it happened in RT's, an inhibitory effect was found for reversible letters on accuracy. Participants were significantly less accurate for both mirrored and rotated prime conditions relative to the control primes, $t_1(33) = -2.81$, $d_z = 0.49$, $p = .008$ ($t_2(191) = -2.14$, $p = .033$) and $t_1(33) = -3.05$, $d_z = 0.53$, $p = .004$ ($t_2(191) = -3.86$, $p < .001$), respectively, For nonreversible letters, participants responded more accurately in the mirrored prime condition, compared to control primes, $t_1(33) = 3.15$, $d_z = 0.55$, $p = .003$ ($t_2(191) = 1.92$, $p = .057$), but no significant difference was found between control and rotated prime conditions, $t_1(33) = -1.05$, $d_z = 0.18$, $p = .30$ ($t_2(191) = -1.02$, $p = .31$).

As previously mentioned, Experiment 2 was developed to ensure that the results reported in the present experiment were not due to top-down interference from the word level (McClelland & Rumelhart, 1981). As suggested by Norris and Kinoshita (2008), the relation between prime and target is not a fixed property, and the need to identify the presence of a word during lexical decision, hence lexical activation, could interfere with letter recognition. By adopting a *same-different* task with masked priming in Experiment 2, it should be possible to reduce lexical activation effects while examining prelexical aspects of orthographic processing, such as letter identification (Norris & Kinoshita, 2008, 2012).

3. Experiment 2

3.1. Method

3.1.1. Participants

Thirty-six fresh undergraduate students from Universidade de Lisboa (5 males, M_{age} 18.8, SD = 0.9) took part in this experiment in exchange for a course credit after giving informed consent. They had the same characteristics as the participants of Experiment 1 and the same exclusion criterion applied: One woman was excluded due to low performance (average accuracy of 49%) in *different*-response trials.

3.1.2. Design

Experiment 2 adopted a same-different task with the masked priming paradigm, in a 2 (same vs. different) x 2 Letter type (reversible vs. non-reversible) x 4 Prime condition (identical; mirrored; rotated; control) design. RTs for correct responses and accuracy were measured.

3.1.3. Material

For this experiment, only lexical items were used, half of each corresponded to the words used in Experiment 1. For *same*-response trials (50% of the total trials in the experiment), the 384 words of Experiment 1 were presented. The *different*-response trials were fillers given that no reliable priming effects have been reported in prior studies adopting the masked paradigm with this task (e.g., Perea, Moret-Tatay, & Carreiras, 2011). For *different*-response trials, a new set of 384 words was selected, divided into two sets of 192 items each, with the critical letter being a reversible letter for one set and a non-reversible letter for the other set. The words used in *different*-response trials (presented in Appendix) had the same characteristics of those in *same* trials: 4-9 letters, 2-4 syllables long. The position of the critical letter occurred on average, similarly to *same*-

response trials, at the middle letter position within-word, matched between reversible and non-reversible sets, *t*(382) = -1.79, *p* = 0.07.

For all items, a lowercase version was created to be used as a reference, and an uppercase version to be used as target. The same procedure as in Experiment 1 was used to create the four prime conditions, that is, control, identical, mirrored, and rotated.

3.1.4. Procedure

Each trial started with the presentation of a reference word, above a nine-cardinal string for 1s, followed by the masked prime for a duration of 48ms (3 refresh cycles) that appeared in the location of the nine-cardinal string. Immediately after the prime, and in the same position, the target was presented until the participant's response or until 2500 ms had elapsed, as shown in Figure 4.

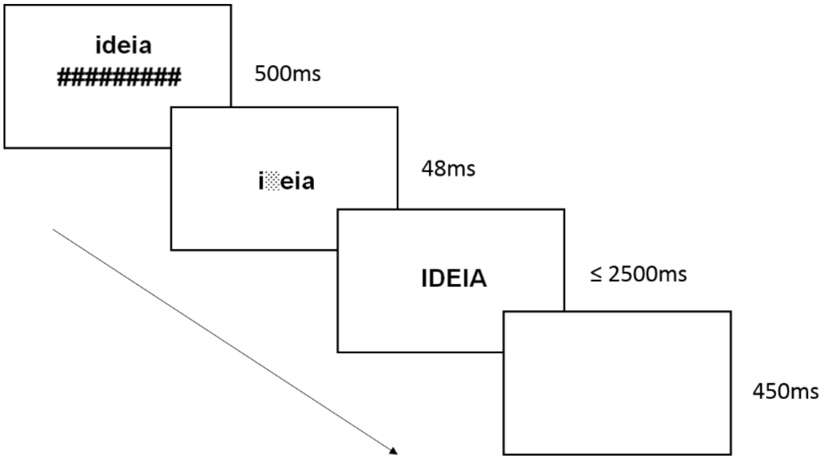

Figure 4: Procedure used in the same different task

Illustration of sequence of events for each trial. Example of a same-response trial for a reversible letter item in the control prime condition.

Participants were instructed to decide as accurately and as fast as possible if the target and the reference words were the same or different, regardless of case, by pressing the number keys "5" (for yes) and "1" (for no) with their right and left index fingers, respectively. The presence of primes was not mentioned, and to make sure participants understood the task, they performed a 16-trial practice list with feedback on accuracy and RT.

Previous studies have shown no significant priming effects for *different*-response trials (e.g., Perea, Moret-Tatay, & Carreiras, 2011), therefore, these were used as fillers. For these trials, a zero-contingency procedure was used to avoid response bias in relation to reference-prime contingency (cf. Perea, Moret-Tatay, & Carreiras, 2011). To this aim, in half of the trials, the prime differed from the reference on the critical letter only (i.e., prime was in relation to the reference), and for the other half, the prime would differ from the target in the critical letter only (i.e., prime was in relation to the target). This way, a response bias for *different*-response trials is eliminated, given that participants response cannot depend solely on the similarity between prime and reference.

As in Experiment 1, four experimental lists were created for counterbalancing purposes. Each participant performed only one of the four lists and every target appeared only once per experimental list, while all items were presented in the four prime conditions, across lists, and between participants.

3.2. Results and Discussion

The same trimming procedure as in Experiment 1 was used (2.54% of data excluded). ANOVAs were run on *same* trials with 2 Letter type (reversible; nonreversible) x 4 Prime condition (control; identical; mirror; rotation), separately for mean accuracy and correct RTs (see Table 2).

Table 2 Participants mean response times (in ms) and percent correct responses (in parentheses) for same and different response trials in the same-different task.

	Prime Condition			
	Control	Identical	Mirrored	Rotated
Same				
Reversible letters	478 (93.5)	474 (94.6)	483 (93.6)	488 (90.9)
Nonreversible letters	489 (93.7)	478 (93.8)	479 (93.4)	486 (93.1)
Different				
Reversible letters	516 (94.8)	515 (94.0)	518 (95.4)	513 (95.9)
Nonreversible letters	520 (96.1)	518 (94.9)	513 (95.1)	509 (96.4)

RTs for correct *same* responses

A significant interaction was found in RT between letter type and prime condition, $F_1(3, 102) = 4.74$, $p < .005$, $\eta p^2 = .12$, $MSE \sim 0.00$ ($F_2(3, 1146) = 1.00$, $p < .396$ $\eta p^2 = .003$, $MSE = 0.01$). The main effect of prime condition was also significant, $F_1(3, 102) = 9.92$, $p < .001$, $\eta p^2 = .23$, $MSE \sim 0.00$ ($F_2(3, 1146) = 7$, $p < .001$, $\eta p^2 = .018$, $MSE = 0.01$), and there was no main effect of letter type, $F_1(1, 34) = .05$, $p = 0.83$, $\eta p^2 = .001$, MSE ~ 0.00, $F_2(1, 382) = 0.00$, $p = .98$, $\eta p^2 \sim 0.00$, $MSE = 0.01$. Participants were significantly faster on *same* trials, when the target was preceded by an identical prime than by a control prime, $F_1(1, 34) = 5.69$, $p = .023$, $\eta p^2 = .14$ ($F_2(1, 382) = 2$, $p = .17$, $\eta p^2 = .005$), and this effect was not modulated by letter type, $F_1(1, 34) = .82$, p

= .37, $\eta p^2 = .02$ (F_2 (1, 382) = 0.00, $p = .52$, $\eta p^2 = .001$). However, both effects of mirrored priming and rotated priming were modulated by letter type, F_1(1, 34) = 5.2, $p = .029$, $\eta p^2 = .13$(F_2 (1, 382) = 2, $p = .17$, $\eta p^2 = .005$), and F_1(1, 34) = 10.92, $p = .002$, $\eta p^2 = .24$ (F_2 (1, 382) = 3, $p = .11$, $\eta p^2 =$ .007), respectively. As it happened in Experiment 1, rotated primes resulted in significantly slower word decisions than mirrored primes, F (1, 34) = 15.3, $p <.001$, $\eta p^2 = .31$ (F_2(1, 382) = 9, $p \sim .003$, $\eta p^2 = .02$), and this effect was again not modulated by letter type, F (1, 34) = 2.1, $p \sim .16$, $\eta p^2 \sim$ .06 (F_2(1, 382) = 0, $p \sim .76$, $\eta p^2 \sim .00$). Again, letter identification seems to be influenced by orientation, with rotated letters introducing more noise in letter identification than mirrored letters, given that the discrimination of these orientation contrasts relies on different properties of the visual system.

For reversible letters, an orientation contrast effect was found, F_1(2, 68) = 21.13, $p < .001$, $\eta p^2 = .38$ (F_2 (2, 382) = 7, $p < .001$, $\eta p^2 = .036$), with orientation contrasts (i.e., mirrored and rotated primes) leading to significantly slower responses than identical primes: vs. mirrored prime, t_1(34) = -2.55, $d_z = .44$, $p = .015$ (t_2(191) = -1.27, $p = .21$); vs. rotated prime, t_1(34) = -6.18, $d_z =$ 1.05, $p < .001$ (t_2(191) = -4.09, $p < .001$). However, when compared with controls, mirrored primes did not inhibit target response, t_1(34) = -1.08, $d_z = .18$, $p \sim .29$ (t_2(191) = -.92, $p = .36$), whereas rotated primes lead to significantly slower responses, hence inhibition, t_1(34) = -4.26, $d_z = .73$, $p <$ .001 (t_2(191) = -3.35, $p < .001$). This result, contrasting the inhibitory effect observed for mirrored reversible letters in Experiment 1, suggests that top-down feedback from the word level might assist in the discrimination of mirrored letters (e.g., differentiating *d* and *b*), instead of a specific mechanism of mirror-image suppression for reversible letters (Perea, Moret-Tatay, & Panadero, 2011). For nonreversible letters no difference was found between identical primes and the two orientation contrast primes (i.e., mirrored; rotated), F_1(2, 68) = 2.26, $p = .11$, $\eta p^2 = .06$ (F_2 (2, 382)

= 3, p =. 033, $\eta p^2 = .018$). Therefore, facilitation for mirrored primes of nonreversible letters cannot be solely explained by a mechanism of mirror invariance, since rotated primes produced the same facilitatory effect, and the ventral visual stream is originally sensitive plane-rotation contrasts.

Accuracy

On accuracy, the main effect of prime was significant, $F_1(3, 102) = 5.17$, $p = .002$, $\eta p^2 = .13$, $MSE \sim 0.01$ ($F_2(3, 1146) = 5.28$, $p = .001$, $\eta p^2 = .013$, $MSE = 0.04$), but neither the main effect of prime condition, $F_1(3, 102) = 1.89$, $p = .136$, $\eta p^2 = .05$, $MSE \sim 0.01$ ($F_2(3, 1146) = 1.80$, $p = .145$, $\eta p^2 = .005$), nor the interaction between the two factors, $F_1(1, 34) = 0.62$, $p = .44$, $\eta p^2 = .018$, $MSE \sim 0.01$ ($F_2(1, 382) = 0.64$, $p = .42$, $\eta p^2 = .002$, $MSE = 0.04$). As it was observed in RTs, only reversible letters letter were affected by orientation contrasts, $F_1(2, 68) = 8.13$, $p < .001$, $\eta p^2 = .19$ ($F_2(2, 382) = 9.54$, $p < .001$, $\eta p^2 = .048$,), with worse participants' accuracy for *same* response trials when target was preceded by either a mirrored or rotated prime, relative to identical primes. Nonreversible letters were not affected by orientation contrasts, when compared to identical primes, $F_1(2, 68) = .236$, $p = .79$, $\eta p^2 = .007$ (F_2 $(2, 382) = 0.68$, $p = 0.50$, $\eta p^2 = .003$).

The overall effects reported in Experiment 2, although less robust, converged with those of Experiment 1 and were consistent with the proposed hypothesis. Reversible and nonreversible letters were similarly affected by orientation contrasts (mirrored and rotated) during target word recognition. Once again, if facilitation for mirrored primes of nonreversible letters relied on a mechanism of mirror invariance, as previously suggested (Perea, Moret-Tatay, & Panadero, 2011), the rotated version of nonreversible letters should have interfered with target recognition, since the visual system is originally sensitive to plane-rotation contrasts (Logothetis et al., 1995). Furthermore, following the suggestion that the inhibitory effects found for mirrored versions of reversible letters are due to active suppression of mirror images, the rotated version of reversible letters should have led to either facilitation of target recognition (due to similar letter substitution; Perea, Moret-Tatay, & Panadero, 2011; Experiment 1) or to reduced inhibition, when compared to the mirrored version (since we used an absent letter control prime instead of a letter substitution control). Instead, the pattern of results in both experiments seems to be congruent with IA's account regarding activation of letter nodes most compatible with the input. Indeed, visual similarity and feature sharing between nonreversible letters and their orientation contrasts (incompatible with other letter nodes) can explain the facilitatory effects found for nonreversible letters, while inhibitory interactions between letter nodes of reversible letters and their orientation contrasts (incompatible with the target critical letter and target word) should account for the inhibitory effects produced by orientation transformations of reversible letters.

4. General Discussion

In the present study, we conducted two experiments to explore the early mechanisms involved in visual word recognition, and specifically, to tap into the early stages of orthographic processing: how the cognitive system computes letter features into abstract letter identities. For this purpose, the two experiments adopted the masked priming paradigm (differing only by task: Experiment 1, lexical decision; Experiment 2: same-different task, albeit both tap in early processing) and we manipulated the orientation-transformation of critical (reversible and nonreversible) letters embedded in words. Critical letters were manipulated in four prime conditions: an identical prime, a control prime and two critical orientation transformation primes (mirrored and rotated) for which discrimination relies on two different properties of the visual system (i.e., mirror-image discrimination acquired only through literacy and plane-rotation discrimination being inherent).

The main original contribution of the present study can be summarized as follows: during the early stages of word recognition, skilled readers are sensitive to mirror images of letters, regardless of letter type (for both reversible and nonreversible letters, contrary to the suggestion of Perea, Moret-Tatay, & Panadero, 2011) and despite this discrimination not proving any advantage towards nonreversible letter identification.

In agreement with the neuronal recycling hypothesis (Dehaene, 2004) and previous literature on the impact of literacy on non-linguistic object recognition (e.g., Fernandes & Kolinsky, 2013), the adaptation of evolutionary-older functions to accommodate cultural advances (e.g., overcoming mirror invariance to discriminate mirrored symbols of a script) seems to operate even when it may not necessarily be advantageous. Along the same line, the pattern of results for the mirrored-letter version of critical letters in primes (i.e., facilitation for nonreversible and inhibition for reversible letters) was similar to that of rotated-letters, for which discrimination relies on an original property of the ventral visual stream (i.e., plane-rotation discrimination; Logothetis et al., 1995). Thus, the mirrored priming effects described here and previously reported by Perea, Moret-Tatay, and Panadero (2011), regarding discrimination of reversible and nonreversible letters transformed to their mirrored version, do not seem to follow from a specific mechanism of mirror-invariance suppression for reversible letters (specific to this orientation contrast) and that does not apply to nonreversible letters, for which, according to Perea, Moret-Tatay, and Panadero (2011) mirror invariance would still operate early on.

Therefore, the presented results of both experiments are compatible with theoretical assumptions of contemporary computational models of visual word recognition. According to the IAM, a letter node is activated when the perceived features of an input are compatible with that letter's abstract representation (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). Given that reversible letters share all the features and overall visual shape between them, when transformed to their mirrored or rotated versions in the prime they will activate multiple letter nodes (compatible with the input's features) that compete for recognition, interfering with target response. For nonreversible letters, the activation of multiple letter nodes does not occur since the base letter node is the only one compatible with the presented features and overall visual shape of the input. In a different perspective and following the Bayesian approach, the orientation transformation of reversible letters in the prime interferes with target recognition because the output sample generated from the prime's input increases the likelihood (probability) of a different letter being present in the critical letter position. This does not occur for nonreversible letters since the input most likely to have generated the output sample (i.e., the mirrored or rotated letter in the prime) is the original letter itself.

More recently we developed an experiment using the sandwich priming paradigm where we recorded electrophysiological data (i.e., *evoked response potentials,* ERP) during recognition of target words primed by the same conditions presented in this study (i.e., control, nine dot pattern; identical; mirrored; rotated). When planning this experiment, we attempted to overcome possible limitations that the sandwich priming paradigm might entail. Specifically, the lowercase version of targets that appeared immediately before primes (see Method; Experiment 1) was presented in uppercase, excluding low-level perceptual differences between prime conditions and the lowercase version of targets as a possible explanation for our results. Indeed, even though we equated critical letters and their transformed versions for perceptual confusability in a pre-test, this relation could possibly change when the letters are presented within words. On a different note, the analysis of the different ERP components, associated to the different orientation contrasts of reversible and nonreversible letters during word recognition, will allow to better understand the different levels of processing (i.e., prelexical vs. lexical) that operate during letter identification and how they are influenced by orientation contrasts.

An important aspect that could be considered in future research, given the smaller priming effect found for the 180º plane-rotation transformation relative to mirror images (either facilitatory or inhibitory effects for nonreversible and reversible letters, respectively), is that the 180º plane-rotation changes the ascending-descending relation property relative to the original letter, which does not occur for the mirror image. For illustration, when rotated on the picture plane, ascending letters such as *d* and *b* become descending (e.g., *p* and *q*) and vice-versa (e.g., transformation from "**cauda**" to "**caupa**"), whereas this change of letter position in relation to the word does not happen when the letter is mirrored. This could be one of the reasons for the difference in the magnitude of priming for mirrored and rotated letters that we found. Indeed, Perea and Panadero (2014) showed this sensitivity to the shape of the letter, at least in disfluent readers. Furthermore, we have found the same qualitative pattern of priming effects for mirrored and rotated primes of reversible letters (both being inhibitory) and of nonreversible letters (both being facilitatory), which suggests that feature sharing might be stronger than the pattern of ascending/descending features. Also, we recently adopted a same-different task on isolated letters[2], rendering the ascending-descending property of letters less relevant (since no visual cues could assist in discriminating whether the letter goes upward or downward in relation to the other letters present in a word), and the pattern of priming effects for orientation contrasts of reversible and nonreversible letters was similar to the ones presented in this study.

Although we tried to control for lexical interferences in both experiments as far as possible, the development of a task where words are presented that completely dissociates prelexical processes form lexical effects is a challenge (Kelly, van Heuven, Pitchford, & Ledgeway, 2013) and recent research argues in favor of both the masked priming allied with the same-different task and the sandwich priming with lexical decision taping mostly on early orthographic effects. However, top-down influences might still operate, even if residual. An apparent solution would be to avoid presenting words in experiments that focus on prelexical aspects of word recognition (Kelly et al., 2013). However, creating such tasks (either by using non-word letter strings or isolated letters) to explore prelexical mechanisms involved in orthographic processing would arguably lose its purpose, since these processes would no longer occur in respect to visual word

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[2] We adopted the *letter match* task (cf. Kinoshita & Kaplan, 2008) on isolated letters (i.e., the same-different decision was made on letters omly) and using the same critical letters and prime conditions presented in this study (i.e., control, nine-dot-pattern; identical; mirrored; rotated).

recognition per se. Indeed besides letter identification, letter position is also relevant during orthographic processing, as the transposed letter effects have shown (strong priming effects when BRAIN is primed by brian or CASINO by caniso; e.g., Perea & Lupker, 2004). The use of high temporal resolution measures such as event-related potentials can contribute to this research.

In conclusion, we showed that during the early stages of processing, visual word recognition operates under the same principles of non-linguistic object recognition, being affected in the same way by orientation contrasts. Future revisions of contemporary models of visual word recognition should attempt to modify the practical parameters that govern feature-to-letter and within letter level interactions in consideration with the basic properties of the structures that support reading.

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Appendix

Table 3 Descriptive statistics (Mean and SEM) on the psycholinguistic characteristics of word items used in Experiment 1 and Experiment 2 for same-response trials.

	Reversible letter set	**Non-reversible letter set**
Word length (number of letters)	5.49 (0.07)	5.66 (0.08)
Position of critical letter	2.89 (0.09)	2.93 (0.10)
Word Frequency (log)	5.93 (0.12)	5.83 (0.11)
Orthographic Density	3.29 (0.26)	3.22 (0.29)
Phonological Density	3.31 (0.26)	3.16 (0.29)
Orthographic Unicity Point	5.19 (0.08)	5.37 (0.09)
Phonological Unicity Point	4.80 (0.08)	4.81 (0.08)

Table 4 List of word items used in Experiment 1 and Experiment 2 for same-response trials.

Non-reversibe letter word set			
ABRIGO (shelter)	CANTO (corner)	FILHO (son)	RAIVA (anger)
AFASTAR (*to* remove)	CARA (face)	FILME (film)	RALHAR (scold)
AFINAL (after all)	CARINHO (affection)	FLEXÃO (flexion)	RAMO (branch)
AFLIÇÃO (distress)	CARNE (meat)	FOFO (cute)	RARO (rare)
AGENTE (agent)	CARTA (letter)	FOGUETÃO (rocket)	RATO (mouse)
AGORA (now)	CASTANHA (chestnut)	FORNO (oven)	RAZÃO (reason)
ALARME (alarm)	CASTELO (castle)	FRACO (weak)	RECADO (message)
ALEGRE (joyful)	CASTIGO (punishment)	FRESCO (fresh)	RECOLHER (*to* retract)
ALERGIA (allergy)	CENTENA (hundred)	FRIO (cold)	REDE (net)
ALFACE (lettuce)	CESTO (basket)	FRUTA (fruit)	REFEIÇÃO (meal)
ALMOFADA (pillow)	CHEFE (chief)	FUMO (smoke)	REFLEXO (reflection)
ALTO (tall)	CHEIRO (smell)	FUTURO (future)	REFORMA (reform)
ALTURA (height)	CHIFRE (horn)	GARFO (fork)	REGRA (rule)
AMORA (blackberry)	CINTO (belt)	GERAL (general)	RESTO (rest)

AMOSTRA (sample)
ANTENA (antenna)
ANTIGO (old)
AQUÁRIO (aquarium)
ARAME (wire)
ARANHA (spider)
ARBUSTO (bush)
ARCO (arc)
ARENA (arena)
ARMA (weapon)
ARTE (art)
ARTIGO (article)
ÁRVORE (tree)
ASSALTO (robbery)
ASTRO (star)
ATAQUE (attack)
ATLETA (athlete)
ATUM (tuna)
AZEITE (olive oil)
BARATA (cockroach)
BATA (smock)
BATOTA (cheating)
BIFE (steak)
BOLOR (mold)
BORLA (free)
BOTA (boot)
BOTIJA (jar)
BREVE (brief)
BRILHO (shine)
CIRCO (circus)
COFRE (safe)
CONTA (account)
CONTIGO (with you)
CONTROLO (control)
CORAÇÃO (heart)
CORTE (cut)
COSTAS (back)
CRÈME (cream)
CREPE (crepe)
CRUZ (cross)
CURSO (course)
DEFEITO (defect)
DEFESA (defense)
DIFICIL (hard)
DISFARCE (disguise)
DURO (hard)
ECRÃ (screen)
EFEITO (effect)
ERVA (grass)
ESFERA (sphere)
ESFREGÃO (mop)
ESPERA (waiting)
ETERNO (eternal)
FALAR (*to* speak)
FARINHA (flour)
FAROL (lighthouse)
FATO (suit)
FAZER (*to* do)
GORILA (gorilla)
GRANDE (big)
HORA (hour)
IGREJA (church)
INFERNO (hell)
LARANJA (orange)
LETRA (letter)
LIVRE (free)
LIVRO (book)
MANTEIGA (butter)
MARCA (brand)
MARFIM (ivory)
MORADA (address)
MORNO (warm)
MORTE (death)
NARIZ (nose)
NEGATIVA (negative)
NEGRO (black)
OFERTA (offer)
OMBRO (shoulder)
PANFLETO (pamphlet)
PATRÃO (boss)
PEGAR (catch)
PERFEITO (perfect)
PERFUME (perfume)
PIRATA (pirate)
PORTA (door)
PRIMO (cousin)
PROFESSOR (teacher)
RESUMO (resume)
REUNIR (join)
RICO (rich)
RIFA (raffle)
RIMA (rhyme)
RISCO (risk)
SALÁRIO (salary)
SECRETO (secret)
SEGURO (secure)
SENHORA (lady)
SOFÁ (couch)
SOFRER (*to* suffer)
SOPRO (blow)
SORTE (luck)
TABACO (tobacco)
TANGO (tango)
TARDE (late)
TAREFA (task)
TEATRO (theatre)
TERROR (horror)
TESOURO (treasure)
TIGRE (tiger)
TINTA (ink)
TOMADA (socket)
TRANÇA (braid)
TRIGO (wheat)
TRINTA (thirty)
TRISTE (sad)
TRIUNFO (triumph)

BROA (corn bread)
BRUTO (rude)
CACIFO (locker)
CADERNO (notebook)
CAIXOTE (box)
FEIJÃO (been)
FERA (beast)
FERIDA (wound)
FICHA (recording)
FIGURA (figure)
PROVA (proof)
PURÉ (mashed potato)
RÁDIO (radio)
RAFEIRO (mongrel)
RAINHA (queen)
TRUNFO (trump)
VAMPIRO (vampire)
VARA (stick)
ZERO (zero)
RAIO (lightening)

Reversible letter word set

ABELHA (bee)
ABERTO (open)
ABRAÇO (hug)
ABRIL (April)
ABRIR (*to* open)
ACABAR (*to* finish)
ADEUS (goodbye)
ADIAR (*to* postpone)
ADIÇÃO (addition)
ADULTO (adult)
AGUDO (acute)
ÁLBUM (album)
ALGODÃO (cotton)
APITO (whistle)
APOIO (support)
APOSTA (bet)
APRENDER (*to* learn)
ASPAS (quotation marks)
BAILE (prom)
BALCÃO (counter)
BALDE (bucket)
BANDEIRA (flag)
CARAPAU (mackerel)
CARDUME (shoal)
CAUDA (tail)
CEBOLA (onion)
CEDO (early)
CÉREBRO (brain)
CIDADE (city)
CLUBE (club)
COBRA (snake)
COMIDA (food)
CONDE (count)
CÓPIA (copy)
COPO (glass)
CORDA (rope)
CUBO (cube)
DADO (dice)
DEBATE (debate)
DEDO (finger)
DEIXAR (*to* leave)
DENTE (tooth)
DEPOIS (after)
DESCULPA (sorry)
ESPIRRO (sneeze)
ESPUMA (foam)
ESTRADA (road)
FADA (fairy)
FARDA (uniform)
FEBRE (fever)
FRALDA (diaper)
FUNDO (bottom)
GLOBO (globe)
GOLPE (blow)
GORDO (fat)
GRADE (grid)
GRIPE (flu)
GUARDA (guard)
IDADE (age)
IDEIA (idea)
ÍDOLO (idol)
IDOSO (elder)
ÍMPAR (odd)
JUDO (judo)
LADO (side)
LÁPIS (pencil)
PASTA (paste)
PEDAÇO (piece)
PEDIR (*to* ask)
PENA (feather)
PERDÃO (pardon)
PIADA (joke)
PIPA (barrel)
PODER (power)
PODRE (rotten)
PRÓPRIO (own)
PUDIM (pudding)
QUADRO (painting)
RAMPA (ramp)
RAPAZ (boy)
RAPOSA (fox)
REDONDO (round)
RENDA (income)
REPETIR (*to* repeat)
RESPEITO (respect)
RODA (wheel)
RODELA (slice)
ROUBAR (*to* steel)

BARBA (beard)
BARRA (bar)
BATALHA (battle)
BEBIDA (drink)
BICICLETA (bicycle)
BILHETE (ticket)
BOCADO (bit)
BOLA (ball)
BOMBA (bomb)
BOMBOM (bonbon)
BORBULHA (pimple)
BOTÃO (button)
BRANCO (white)
BRINDE (toast)
CABEÇA (head)
CABEDAL (leather)
CABELO (hair)
CABIDE (hanger)
CABO (cable)
CABRA (goat)
CADEIRA (chair)
CALDO (broth)
CAMPO (field)
CANSADO (tired)
CAPITAL (capital)
CAPITÃO (captain)
DESEJO (desire)
DESPORTO (sport)
DEVER (duty)
DIABO (devil)
DIETA (diet)
DISCO (disk)
DITADO (saying)
DIZER (*to* tell)
DOBRAR (*to* double)
DOBRO (twice)
DOCE (sweet)
DOIDO (crazy)
DOMINGO (Sunday)
DOURADA (golden)
DOUTOR (doctor)
DRAGÃO (dragon)
DROGA (drug)
DUCHE (shower)
DUPLO (double)
DÚVIDA (doubt)
EQUIPA (team)
ESPAÇO (space)
ESPADA (sword)
ESPERTO (smart)
ESPIÃO (spy)
ESPINHA (fishbone)
LENDA (legend)
LUPA (magnifying glass)
MADEIRA (wood)
MAPA (map)
MEDALHA (medal)
MÉDICO (physician)
MEDO (scare)
MODA (fashion)
MOEDA (coin)
MORDER (*to* bite)
MUDO (mute)
MUNDO (world)
NADA (nothing)
NADAR (*to* swim)
NOBRE (noble)
OBRA (work)
ODIAR (*to* hate)
ONDA (wave)
ORDEM (order)
PACOTE (package)
PADRE (priest)
PALCO (stage)
PALPITE (hint)
PAPA (pope)
PAPEL (paper)
PARQUE (park)
SÁBADO (Saturday)
SABÃO (soap)
SABER (*to* know)
SABOR (flavor)
SALADA (salad)
SAPATO (shoe)
SEDA (silk)
SOBRE (about)
SOLDADO (soldier)
SUBIR (*to* rise)
SURDO (deaf)
SURPRESA (surprise)
TAMPA (cover)
TAPAR (*to* close)
TEMPO (time)
TENDA (tent)
TODO (all)
TOLDO (awning)
TORRADA (toast)
VAPOR (steam)
VENDA (sale)
VERBO (verb)
VERDE (green)
VIDA (life)
VIDEO (video)
VIDRO (glass)

Table 5 List of nonwords used in Experiment 1

Non-reversibe letter nonword set

AFINGAR
AGORME
ALNIRTA
ARDAZ
ARTELA
ARVO
ASARAVO
ATRINE
AVROJE
BAFLINO
BENTRUIR
BERCE
BESTERE
BINFO
BORECA
BORFO
BOTELA
BRATOR
BREMPA
BRIFAR
BRONE
BURTA
CANFROLE
CASPETE
CAVITO
CETORA
CHAIRE
FANIR
FARLA
FEBEL
FEDOIS
FELO
FENCIPO
FETRA
FEZO
FIBUR
FILORTE
FILTE
FIMONA
FIRILDA
FLOFERROS
FOLRE
FOMOR
FONTIRA
FORÉ
FRICHE
FROZE
FUNRE
FUTER
FUZAR
GADATO
GARIFA
GERIPO
GRAFENHO
JERBE
JIRTA
LECRO
LEREL
LINTEGA
LIRTO
LUBORO
LUFO
LUNHIRO
LURCA
MANTASO
MEUFA
MILRO
MONTRILO
MUFIA
MUNFITO
MURFEITO
NAFEILO
NEFEVA
NERZO
OFELHO
OLTE
ORBROS
ORIVO
ORMO
OSRE
OTRÃ
RAUVER
RAXI
REDRO
REFI
REIO
RELÃO
RENCO
RETUFA
RIMERA
RINFOL
RIRFE
ROFÉ
ROGE
ROTILA
ROZI
RUGRE
RULIO
RUNER
SAFRE
SAROR
SOFIRO
TADEIRO
TARÉ
TASDE
TASURA
TEMPRA
TEROA

CHANIFO
CHARI
CIFOLHO
CIPRO
CISTAL
DATUCA
DEFEICIL
DEFORÇÃO
DEGRE
DIFEPLO
DILATIVA
DURÇÃO
DURDE
DURFO
EFORTAS
ERZE
ESCOTOR
ESRO
ESTARO
ETIL
XERU
GREZ
GRIRA
GRONA
GUDOFO
HORU
IFLERA
IFTA
IFUNAL
ILERO
INFULA
INTA
IPRÕ
IRANA
IRGO
IROLHO
IRTAFALO
ITERFE
IVARE
JALERO
JARTENO
ZARONA
PAFI
PAGASTO
PALURO
PAMBERA
PANFIM
PARELA
PEFREDO
PERTOLHA
PIRENTA
PIROLA
PRIE
PRORE
PROXE
PRURANO
RAINFO
RAIZE
RALIPE
RALODER
RANO
RARDO
ZIRE
TESPO
TIFE
TIGOCA
TOLGRIA
TONFE
TREFES
TRENGO
TRILE
TROA
TRUDOI
TUFUREO
TURESO
TUSSEL
URGOL
URTRÃE
UTILBO
VAFLOÇA
VEQUITÃO
VESTRA
VOLETO
ZOVRO

Reversible letter nonword set

ÁLIDO
ALPERTE
AMBO
AMPEZ
ANIBAR
DELFO
DERCO
DETIM
DIACHE
DIÁTIO
DIRBA
DIRRELE
DITABRA
DOFER
DOFO
IFEDA
ILOIA
IMBRIJA
IMPARDO
INGAR

APASÃO
ARINDA
ASDOS
ASPUZ
ATEPO
AUDIZ
BALDINA
BANFA
BARBILHO
BAZATA
BELÃO
BERLADOS
BILHODE
BILO
BIRTÃO
BOCO
BOLHOTA
BRAPE
BRIZO
BROJO
BUCLERIT0
CALDIDE
CASDO
CEDAL
CEDAVE
CEPER
CHODE
CIDER
CILPE
DICUBO
DIEDO
DILMOR
DIOBO
DIRBA
DIRRELE
DITABRA
DOFER
DOFO
DOMBATO
DONTIR
DOPITA
DRUJA
DUÇÃO
DUDIR
DUJÃO
DURCAR
EBIVÃO
EDAXÃO
EGIAR
EMBIDE
EMBO
EMPE
EMPICA
ENDO
EPEVA
ÉPOLA
ESBIO
ESBUR
DOMBATO
DONTIR
DOPITA
DRUJA
DUÇÃO
DUDIR
DUJÃO
DURCAR
EBIVÃO
EDAXÃO
EGIAR
EMBIDE
EMBO
EMPE
EMPICA
ENDO
EPEVA
ÉPOLA
ESBIO
ESBUR
ESPENHO
ESPITA
ESPO
FEBAR
FIBA
FIDE
FIPEL
FONO
FRÉDIA
IPLORER
IRPE
JANDA
LABENA
LADONHA
LEDRO
LESPO
LIPROMA
LOBAR
LODRA
MAIDE
MALDO
MARPEIRA
MINDULA
MONDA
MORBE
MUDIRÃO
NEBRO
NIPELA
NIPEPO
NISDA
NOBOR
ODAPO
ODEDA
OLDA
OMPER
ONIGE
OPIDO
ORPI

CIPAZ	ESPENHO	FRUDO	PADE
CRANDI	ESPITA	FUPAR	PEDOFA
CRUPELHO	ESPO	FURBO	PEMBO
CUBAL	FEBAR	GADEL	PENCO
CULIDAS	FIBA	GADERO	PIEFA
DABISO	DELFO	GARAPO	PIPOR
DAIGO	DERCO	GARPOILO	PIRSA
DANHEILA	DETIM	GODENO	PITRODA
DAPRINA	DIACHE	GRADIR	POBURO
DARPO	DIÁTIO	GRECIDO	PRIBOM
DASDA	DICUBO	GRIDA	PRISDO
DEBOM	DIEDO	GUDI	PUDLA
DEDEO	DILMOR	GUEDA	PUFI
DEIBAR	DIOBO	IBOLCA	PUGILA

Table 6 List of words used for different-response trials in Experiment 2

Non-reversible letter set			
ADVÉRBIO	AGARRAR	APRESSAR	ALARGAR
APANHAR	AGOSTO	ARARA	ALÉM
AQUILO	AREIA	AROMA	ALÍNEA
BRUXO	BALANÇA	AUTOR	ANIMAR
CALÇAS	BAUNILHA	BANHO	CAMINHO
CANÇÃO	BELO	BATER	CAMPANHA
CARGA	BRINCAR	BODE	CANTEIRO
CARGO	CAIR	BÚFALO	CIMENTO
CARTUXO	CEDRO	CALÇADA	COELHO
CASACO	CENTRO	CARVÃO	COLO
CEIA	CHÁVENA	COISA	CONE
CEREAL	CLORO	COLHER	CORNETA

CHAMADA
CHOQUE
CLARO
CLÍNICO
CONVERSA
CORAL
CRAVO
ESFORÇO
FIRME
FÚNEBRE
GRAÇA
HINO
IMENSO
INTERIOR
LOCAL
MARINHA
MESMA
METRO
MOTIVO
MURAL
NUDEZ
NÚCLEO
OURO
PAUSA
PAUTA
PINGO
PLANO
PRATO
QUEIXO

COTAÇÃO
CRIME
DESERTO
DOENTE
FERRO
FOGÃO
FÍSICA
GREVE
GRUA
HERA
LENHA
LISTA
LUME
LUTA
METAL
MUITA
MÚSCULO
NORTE
PARAGEM
PASSAGEM
PISTA
POLVO
PRAZER
PÁSSARO
QUARTO
RAIZ
RECURSO
REGRESSO
RISCA

CRÂNIO
DEPENDER
DESDE
ESTILO
EXIBIR
FECHAR
FILA
FOME
FRASE
FÉRTIL
GANÂNCIA
GREGO
INÍCIO
INÚTIL
ISOLAR
LIGAÇÃO
LUGAR
MANHÃ
MANUAL
MINHA
NÍTIDO
OSSO
PACATO
PERDA
POBRE
PRESSA
QUEIMADA
ROEDOR
SALTO

CORTIÇA
CRISE
DESSA
DISPENSA
ESCRITOR
ESPARGO
ESTRELA
FARSA
FASE
FEITIO
FINAL
FONTE
GOLFE
HONRA
INTENSO
JANELA
JANTAR
LATA
LAZER
LEVAR
LEVE
MAÇÃ
MOTA
NOIVO
NONO
NOVE
NÁUSEA
OFÍCIO
PERNA

RECENTE
REVOLTA
TEXTO
TOURO
TRIBUTO
URSO
ÉPICO

RÁPIDO
SALMÃO
SEMENTE
SOLÚVEL
SÍMBOLO
VINHO
VISÍVEL

SAPO
SETA
SINAL
TABELA
TEIA
UNHA
VISITA

PRECISO
PÚRPURA
SALIVA
SETE
SÚBITO
TÍTULO
ÁREA

Reversible letter set

ABONO
AFIXAR
APAGAR
ATRITO
BARCO
BICHO
BLOCO
BRINCO
BÁSICA
CAPUZ
CIÊNCIA
COSER
CRINA
CRISTA
CÍRCULO
DERROTAR
DESENHAR
DITADOR
ELEITO
ESTANTE

ABANAR
ACASO
ADIVINHA
ALÍVIO
AMANHÃ
AULA
CAVALO
CHAVE
CORDEL
CORDÃO
CREDO
DATA
DORSO
DÉCIMO
ESTADO
ESTIMA
EXAME
FALTA
FOLGA
GRAVE

ABDÓMEN
ACEDER
ACHAR
ADORAR
APÓS
ATRÁS
AVISO
BACIA
BAIXO
BALA
BANDO
BOLBO
BULE
CAPAZ
CAPOTE
CINCO
CONCELHO
CORPO
DANÇA
DUQUE

ALGUMA
APERTO
APROVAR
AQUELA
ATACAR
ATENTO
AZEDO
BALÃO
BARALHAR
BARULHO
BONECA
BRUMA
BUSCA
BÓIA
CAMADA
CAUSA
CHEQUE
COESO
CÔNCAVO
DONA

FEIRA	IMPÉRIO	ESPIRAL	EDITOR
FETO	JEITO	FAMÍLIA	ESTUDAR
GELADO	LARGO	GOELA	FIBRA
INDICAR	LIXO	GRAMA	FINGIR
LAPA	LOBO	GRELHA	FRASE
LÂMPADA	MACACO	INDÚSTRIA	FRENTE
MARINA	MERCADO	LÁBIO	GRÁFICOS
MÓDULO	MISSA	MAGIA	IMÓVEL
NOME	PANELA	MAXILAR	INSULTO
OPOR	PASSEAR	MELRO	LANCHE
PARTE	PEITO	MINUTO	LINDO
PASSADO	PESCA	MODA	LONGE
PELE	PEVIDE	PADEIRO	LÍNGUA
PICO	POMBA	PANDA	MAIOR
PINHAL	PORQUE	PEDAL	MÁQUINA
PLACA	PRENDA	PESO	NENHUMA
PLANTA	PRÓXIMO	PINTOR	PICADA
POSSE	PUMA	POMAR	PINO
POVO	REDOR	POSTAL	PINÇA
QUIETO	ROCHA	PURO	PRÉDIO
RAPINA	SEMENTE	PÁSCOA	REPOR
RECEIO	SUSTO	PÉTALA	RETIRAR
RODÍZIO	TREMER	RUDE	SINISTRO
ROSA	VACINA	SEARA	SOPA
SENTIR	VALE	SONHO	TEXUGO
TERÇO	VIGOR	VALOR	TORTURA
VISTA	VOLTA	VIAGEM	VÍTIMA
ÁLCOOL	ZINCO	VOCAÇÃO	ÚLTIMA