Flip - Reading processes when reading mirrored script

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Summary

There is a common consensus that orthographic processing is deeply rooted in the structure of the visual system. One central aspect that is particularly important in visual processing is mirror-generalization, which is the tendency to treat visual objects and their mirror-image reversal equivalently. Most lower-case letters of the modern Latin alphabet were designed to be read from left to right and from the top the bottom of a page. Some of these letters, in particular those which have a mirror-image counterpart (e.g., "b", "d", "p", and "q") receive different interpretations, although they have the same shape and differ mainly in their orientation. Young children between the age of 5 to 6 tend to produce spontaneous mirror-confusions of letters, and in particular of those letters which are reversible. This behaviour is thought to be rooted in general visual principles of mirror-generalization and it commonly disappears by the age of 8. Mirror-generalization is thought to occur mainly across the vertical (left-right) axis and it is thought to be unlearned, suppressed or inhibited with reading acquisition. However, recent research using a priming procedure - which taps into early, automatic stages of visual word recognition - has shown that even skilled adult readers unconsciously mirror letters in reading. In this context, it has been shown that words which comprise only non-reversible letters (e.g., e, r, c, s) produce priming effects (i.e. they boost word recognition) whereas words which comprise vertically reversible letters (e.g. b, d, p, q) do not produce priming effects, indicating the presence of some inhibitory effect of reversible letters on word recognition. This raises several questions: First, may the propensity of letters and words to be mirror-confused (their mirror-confusability) be a visual property which moderates the ease with which words can be recognized? Second, are involuntary confusions of letters in reading confined to vertical confusions (e.g. b vs d) or do they also occur across the horizontal (up-down) axis (b vs p)? Third, when mirror-confusions are purposely induced through mirroring the letters within text, can a word be recognized before all its constituent letters are identified? Or are words only recognized once all letters have been identified?

Three studies were designed to tackle these questions. The first was a masked priming study placing special emphasis on the locus and nature of early, automatic

mirror reversals of letters during word recognition in adults. This was done by examining whether both vertically and horizontally mirrored letters produce priming effects on word recognition in two different tasks: one tapping into lexical (lexical decision task) and one tapping into pre-lexical processes (same-different match task). Results show that mirror-priming effects occur across both mirror axes and that they generalize to non-words (which do not have a lexical representation). Furthermore, mirror-priming effects are reduced for targets which comprise confusable letters (e.g., d, b, p, q, f, t, u, n). This indicates that general visual principles of mirror-generalization operate both vertically and horizontally and that mirror-priming effects are pre-lexical by nature. To examine whether a word's mirror-confusability moderates word reading times in adults, study 3 involved three experiments. First, the mirror-confusability of the Latin alphabet was quantified in a letter-based score (Exp 1). Second, the mirror-confusability of target words was quantified and manipulated based on the score and words were categorized as high and low confusability words in a lexical decision task (Exp 2). Third, the eye-movements of participants were recorded as they silently read these high and low confusability words when they were embedded in sentences (Exp 3). The results of study 3 imply that letters vary considerably in their *mirror-confusability* and that a word's average mirror-confusability moderates word reading times in adults. Study 2 addressed the question of whether interference effects induced by mirrored letters are confined to early, visual-orthographic processing of letters or whether they also affect lexical stages of the reading process. Results show that mirroring letters disrupts also later, language related processes on the word level, before individual letters are identified, suggesting that processing is cascaded across levels.

Taken together, the results from the three studies provide a comprehensive overview on the nature and time-course of mirror-confusions in functional reading adults. On the ground of these findings, I present how cascaded models of visual word recognition can account for these mirror-effects in adults across different stages and units of processing. In particular, my findings indicate that during an early, automatic and purely visual stage of processing, letter features are generalized to their vertical and horizontal mirror-image counterpart and that this produces priming effects visual word recognition. During a later stage of visual and orthographic processing, mirroring produces interference effects which permeate to the word level. These interference effects are more pronounced for words with a high mirror-confusability. The dissertation provides comprehensive empirical evidence and a theoretical framework that advances our understanding of *if*, *how* and *when* mirroring letters affects the reading process in adults.

Zusammenfassung

Es besteht ein allgemeiner Konsens darüber, dass die orthographische Verarbeitung tief in der Struktur des visuellen Systems verwurzelt ist. Ein zentraler Aspekt, der bei der visuellen Verarbeitung besonders wichtig ist, ist die sogenannte Spiegel-Invarianz. Das ist die Tendenz, visuelle Objekte und deren Spiegelbild gleichwertig zu behandeln. Die meisten Kleinbuchstaben des modernen lateinischen Alphabets wurden so konzipiert, dass sie von links nach rechts und von oben nach unten gelesen werden können. Dies hat zur Folge, dass einige Buchstaben, vor allem "b", "d", "p" und "q", reversibel sind. Das heißt, dass sie, je nach Ausrichtung, unterschiedlich interpretiert werden, obwohl sie die gleiche Form haben. 5 bis 6-jährige Kinder spiegeln häufig genau diese reversiblen Buchstaben, jedoch auch andere. Dies ist ein bekanntes Phänomen, was allgemeinen, visuellen Mechanismen der Spiegel-Invarianz zugeschrieben wird. Dieses Verhalten verschwindet allerdings meist im Alter von 8 Jahren wieder spontan. Man nimmt an, dass Spiegel-Invarianz hauptsächlich zu Spiegelungen über die vertikale (rechts-links) Achse erfolgt und mit dem Erwerb des Lesens verlernt, unterdrückt oder gehemmt wird. Jüngste Forschungen haben jedoch anhand von Priming-Verfahren - die frühe, automatische Phasen der visuellen Worterkennung untersuchen - gezeigt, dass selbst geübte, erwachsene Leser beim Lesen unbewusst immer noch Buchstaben spiegeln. In diesem Zusammenhang hat sich gezeigt, dass Wörter die nur aus nicht reversiblen Buchstaben bestehen (z. B. e, r, c, s), sogenannte Priming-Effekte erzeugen (d. h. sie fördern die Worterkennung), während Wörter, die reversible Buchstaben enthalten (z. B. b, d, p, q), keine Priming-Effekte erzeugen und dadurch eine gewisse hemmende Wirkung auf die Worterkennung haben. Dies wirft mehrere Fragen auf. Erstens: Könnte die Spiegelanfälligkeit von Buchstaben und Wörtern eine visuelle Eigenschaft sein, die die Effizienz der Worterkennung beeinflusst? Zweitens,

beschränken sich unwillkürliche Buchstabenverwechslungen beim Lesen auf vertikale Spiegelungen (z.B. b vs. d) oder treten solche Spiegelungen auch auf der horizontalen Achse (von oben nach unten) auf (z.B. b vs. p)? Drittens: Wenn Spiegelungseffekte absichtlich durch die Spiegelung der Buchstaben innerhalb eines Wortes herbeigeführt werden, wirkt sich die Spiegelung dann hauptsächlich auf die Erkennung einzelner Buchstaben aus? Oder wird das Wort auch schon erkannt, bevor alle einzelnen Buchstaben identifiziert wurden?

Zur Beantwortung dieser Fragen wurden drei Studien durchgeführt. Die erste war eine maskierte Priming-Studie, bei der der Schwerpunkt auf dem zeitlichen Ursprung des Priming-Effekts von gespiegelten Buchstaben während der frühen, automatischen Verarbeitungsphase lag, sowie auf der Richtung des Priming-Effekts. Dazu wurde untersucht, ob sowohl vertikal als auch horizontal gespiegelte Buchstaben, Priming-Effekte bei der Worterkennung erzeugen können. Dies wurde anhand zweier verschiedener Aufgaben untersucht: Einer Aufgabe, die lexikalischen Prozesse untersucht (Lexikalische Entscheidungsaufgabe) und einer Aufgabe, die prälexikalische Prozesse untersucht (Same-different Match Task). Die Ergebnisse zeigen, dass Spiegel-Priming-Effekte auf beiden Spiegelachsen auftreten und von Natur aus prälexikalisch sind. Insbesondere treten Spiegel-Priming-Effekte auch bei Nicht-Wörtern auf (die keine lexikalische Repräsentation haben), und sie sind reduziert, wenn in den verwendeten Stimuli spiegelanfällige Buchstaben enthalten sind (z.B. d, b, p, q, f, t, u, n). Dies deutet darauf hin, dass allgemeine visuelle Mechanismen der Spiegel-Invarianz sowohl vertikal, als auch horizontal wirken und dass sie einen Einfluss auf prälexikalische Phasen der Wortverarbeitung haben. Um zu untersuchen, ob die Spiegelanfälligkeit eines Wortes die Wortlesezeiten bei Erwachsenen beeinflusst, wurden in Studie 3, drei verschiedene Experimente durchgeführt. Zuerst wurde die Spiegelanfälligkeit des lateinischen Alphabets in einem buchstabenbasierten Score quantifiziert (Exp 1). Zweitens wurde die Spiegelanfälligkeit von Zielwörtern auf Grundlage des Scores quantifiziert und manipuliert, und die Wörter wurden in einer lexikalischen Entscheidungsaufgabe in Wörter mit hoher und in Wörter mit niedriger Spiegelanfälligkeit eingeteilt (Exp 2). Drittens wurden die Blickbewegungen der TeilnehmerInnen aufgezeichnet, während sie diese Wörter, die in Sätze eingebettet worden waren (Exp 3), im Stillen lasen. Die Ergebnisse von

Studie 3 deuten darauf hin, dass Buchstaben in ihrer Spiegelanfälligkeit erheblich variieren und dass die durchschnittliche Spiegelanfälligkeit eines Wortes die Wortlesezeit bei Erwachsenen beeinflusst. Studie 2 befasste sich mit der Frage, ob sich die durch gespiegelte Buchstaben absichtlich herbeigeführten Spiegel-Interferenzeffekte, auf die frühe, visuell-orthografische Verarbeitung von Buchstaben beschränken, oder ob sich solche Spiegel-Interferenzeffekte auch auf die lexikalische Wortverarbeitung auswirken. Die Ergebnisse zeigen, dass sich die Buchstabenspiegelungen auch auf spätere, sprachbezogene Prozesse der Wortverarbeitung auswirken, was auf eine kaskadenartige Verarbeitungsarchitektur der visuellen Worterkennung hindeutet.

Zusammengenommen bieten die Ergebnisse der drei Studien einen umfassenden Überblick über die Art und den zeitlichen Verlauf von Spiegelkonfusionen bei erwachsenen Lesern. Auf der Grundlage dieser Ergebnisse stelle ich dar, wie kaskadierte Modelle der visuellen Worterkennung diese Spiegeleffekte bei Erwachsenen über verschiedene Phasen und Verarbeitungseinheiten hinweg erklären können. Insbesondere deuten meine Ergebnisse darauf hin, dass während einer frühen, automatischen und rein visuellen Verarbeitungsphase, Buchstaben unbewusst vertikal und horizontal gespiegelt werden. In einer späteren Phase der visuellen und orthografischen Verarbeitung, wenn einzelne Buchstaben identifiziert werden, führen Buchstabenspiegelungen zu Interferenzeffekten, die sich bis auf die Wortebene auswirken. Diese Interferenzeffekte sind bei Wörtern mit hoher Spiegelanfälligkeit stärker ausgeprägt als bei Wörtern mit geringer Spiegelanfälligkeit. Die Forschungsarbeit liefert umfassende empirische Belege und einen theoretischen Rahmen, der unser Verständnis darüber erweitert, *ob*, *wie* und *wann* Buchstabenspiegelungen den Leseprozess bei Erwachsenen beeinflussen.

Contents

Chapter 1

General Introduction

1.1 Reading and Mirror-confusions

1.1.1 The Origins of Mirror-confusions in Reading

The Latin alphabetical writing system evolved on the basis of the Greek alphabet, a process which was probably mediated by the Etruscans (Haarmann, 1990). The historical development of the Latin alphabetical writing system suggests that the need to distinguish a letter from its vertical mirror-image counterpart has emerged towards the end of the 8th century. In ancient Greek inscriptions from the 6th century B.C. and also scattered early Etruscan and Latin inscriptions the lines of writing and the letters appeared to be reversed line by line (boustrophedon writing) as represented in Figure 1.1. In boustrophedon writing, orientation was not a diagnostic feature of letters and many letters were symmetrical across their vertical axis. This stands in contrast to most modern European languages in which writing and reading begins always at the same side, mostly the left side. Despite these changes, symmetry is still evident in the modern Latin alphabet and it is mainly a feature of upper-case letters, with a higher prevalence of vertically symmetrical (e.g., A or T) than horizontally symmetrical (e.g., E or B) letters (Morin, 2018). By contrast, most lower-case letters are asymmetric and for lower-case letters orientation is an important diagnostic feature. Interestingly, the lower-case letters are a later development of the Latin alphabetical writing system. They originate in the Carolingian minuscule which is the writing system that survives as the basis of the modern Latin alphabet (Haarmann, 1990). By contrast to the upper-case letters, the lower-case letters were meant to be read from left to right (Wallace, 2011).

This seems to be particularly challenging for children who are not yet proficient readers (i.e. between the age of 5 and 10) and who tend to treat mirror images of letters (e.g. b/d, b/p) and sometimes entire words (e.g. saw and wɒƨ) equivalently. Such mirror-confusions appear in children's writing (Portex et al., 2018; Fischer & Tazouti, 2012; Cubelli & Della Sala, 2009; Cornell, 1985; Aaron & Malatesha, 1974) and reading (Dehaene et al., 2010; Gardner & Broman, 1979; Fischer, Liberman, & Shankweiler, 1978) and include both up-down (horizontal) and left-right (vertical) confusions, whereby vertical mirror-confusions have a higher prevalence and are more persistent than horizontal confusions (Davidson, 1935).

According to Corballis and Beale (1976), mirror-confusions in beginning readers result from an excess in generalization because over the course of evolution, the visual system has incorporated the notion that a mirror-image of an object often corresponds to two views of the same object. This tendency to treat visual objects and their mirror-image reversal equivalently is referred to as mirror-image generalization (Bornstein et al., 1978; Logothetis & Pauls, 1995; Rollenhagen & Olson, 2000), symmetry generalization (Lachmann, 2002; Lachmann & van Leeuwen, 2014) or mirror-invariance (Dehaene et al., 2010, 2015). For reading and writing, however, mirror-generalization is detrimental because it can lead to involuntary reversals of letters.

According to the neuronal recycling hypothesis (Dehaene et al., 2005) mirror-confusions occur during the early stages of reading acquisition because for reading, cortical regions that were initially used for visual object recognition are recycled and re-used for the processing of letters. As a result, pre-literate children process words like other visual objects and thus, letters and words are subjected to be mirror-reversed. Once beginning readers become aware that for letters and words (unlike other visual objects) orientation is a diagnostic feature (e.g. b $\neq$ d), mirror-generalization is progressively unlearned (Dehaene et al., 2005, 2010; Pegado et al., 2011; Pegado et al., 2014a), suppressed (Lachmann, 2002) or inhibited (Ahr et al., 2016; Duñabeitia et al., 2011; Perea et al., 2011) during reading and writing.

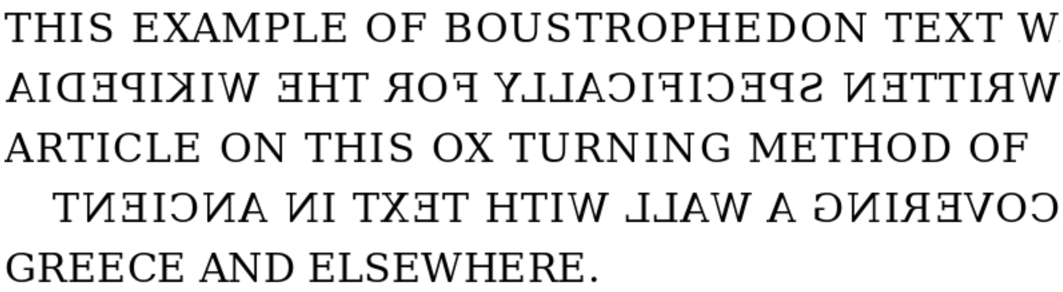


FIGURE 1.1: An example, in English, of boustrophedon as used in inscriptions in ancient Greece (lines 2 and 4 read right–to–left). From Boustrophedon. (2022). Retrieved March 3, 2022, from `https://en.wikipedia.org/wiki/Boustrophedon`

1.1.2 Vertical and Horizontal Mirror-image Confusions

Prior discussions on implicit mirror-confusions induced by general visual principles of mirror-generalization have typically taken for granted that these confusions occur across an extrinsic, vertical axis and there are different explanations for why this should be the case. All of these explanations imply that mirror-generalization enables viewpoint invariant object recognition because it allows to generalize from particular learned experiences to their mirror images (Corballis & Roldan, 1974; Corballis & Beale, 1970). For example, it has been argued that mirror-generalization applies in particular to left-right mirror images because the distinction of mirror-images is irrelevant for determining the identity of an object (Dehaene et al., 2005; Bornstein, 1982; Corballis & Beale, 1976; Gibson et. al., 1962) or because most non-human artefacts are invariant across left–right changes (Bornstein, 1982; Farrell, W. S., 1979; Corballis & Beale, 1976; Sutherland, 1960). Another hypothesis is that mirror-confusions are vertical because visual information is vertically mirror-reversed when stored into memory in a brain that is itself vertically symmetric. According this assumption, memory traces are left-right symmetrized in the process of memory transfer through *interhemispheric mirror-image reversal of memory traces* (Corballis & Beale, 1976) as represented in Figure 1.2. The reason for this is that most of the fibres of the corpus callosum (a bundle of commissural fibre which connects both hemispheres of the brain) are homotopic, which means that they connect the vertical mirror-image point in the other hemisphere (Corballis, 2018).

However, as pointed out by Gregory and McCloskey (2010), the assumption that

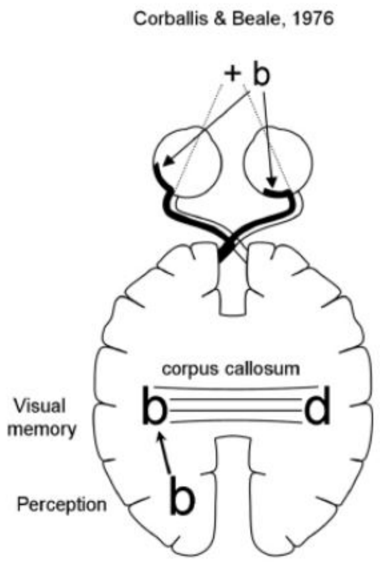
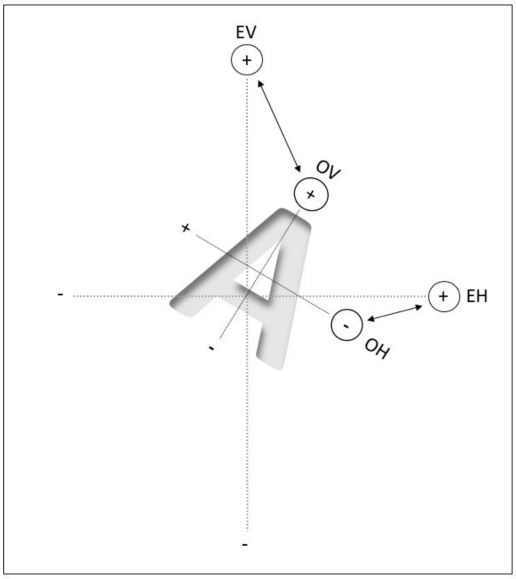


FIGURE 1.2: Interhemispheric mirror-image reversal of memory traces according to Corballis and Beale (1976)

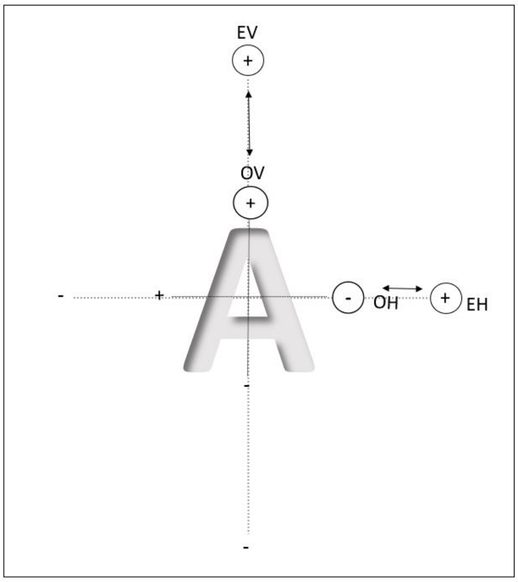
Note: From Dehaene (2009)

mirror-image confusions occur mainly across an extrinsic vertical axis may not be entirely satisfactory because the object identity argument applies equally to other orientations. For example, a bat is still a bat even when presented upside down. Similarly, the reflection of a mountain in a lake - which can often be observed in natural scenes - does not correspond to a different mountain but is a reflection of the same object. According to Gregory and McCloskey (2010) and Gregory et al. (2011), implicit mirror-image confusions occur mainly across any of the two (the horizontal and the vertical) axes of an object and they stem from a failure in encoding, retaining, or processing components of the orientation representations of the two object axes with regard to an external coordinate system. According to the coordinate-system orientation representation (COR) hypothesis (McCloskey, 2009; McCloskey et al., 2006), the orientation of an object is represented as a relationship between an object-centered frame of reference and a second frame of reference which is extrinsic to the object. In the case of letters, the object-centered frame would refer to the letter's vertical mirror axis and the letter's horizontal mirror axis whereas the extrinsic frame of reference corresponds to an external coordinate system with a vertical and a horizontal axis (external reference frame). According to the COR hypothesis, an object's orientation relative to the external reference frame is computed by specifying the relationship between the axes of the object-centered frame and the axes of the external reference frame. For example, the orientation of the letter A in Figure 1.3 a could be represented by relating the object's vertical mirror axis (OV) to the extrinsic vertical axis (EV) and the object's horizontal mirror-axis (OH) to the extrinsic horizontal axis (EH). Each axis has a polarity which is defined as either positive (+) or negative (-). In this model, both the tilt and the polarity correspondences between the object axes and the external axes must be specified. The tilt is represented by indicating the direction and magnitude of the angular displacement between the object's vertical axis and the corresponding extrinsic vertical axis. Thus, for the letter A in Figure 1.3 a the tilt could be coded as: Direction (+) , 45 °. If the letter was tilted anticlockwise, then the tilt could be coded as: Direction (-) , 45 °. The polarity correspondence parameters specify how the polarity of each object axis is related to the polarity of the corresponding extrinsic axis. Thus, for the letter A in Figure 1.3 a, the polarity correspondence would be coded as: Vertical Object Axis (+), Horizontal Object Axis (-). Orientation errors in the COR hypothesis are assumed to result from failures in encoding, retaining, or processing components of these orientation representations. Turning to mirror-image confusions, these are attributed to failures affecting the polarity-correspondence components. For example, consider the letter A in 1.3 b. If the polarity correspondence between the letter's vertical axis and the extrinsic vertical axis were misrepresented as negative to positive (negative vertical object axis pole corresponding to positive external vertical axis pole) the result would be a mirror reflection of the letter A across its horizontal axis (see Figure 1.3 c). If, by contrast, the polarity correspondence between the letter's horizontal axis and the extrinsic horizontal axis were misrepresented as positive to positive (positive horizontal object axis pole corresponding to positive external horizontal axis pole) the result would be a mirror reflection of the letter A across its vertical axis (see Figure 1.3 d). The authors argue that because the representations of the mirror-image orientations are nearly identical and they are distinguished only by the value of a single polarity correspondence parameter, mirror-images are particularly prone to confusions.

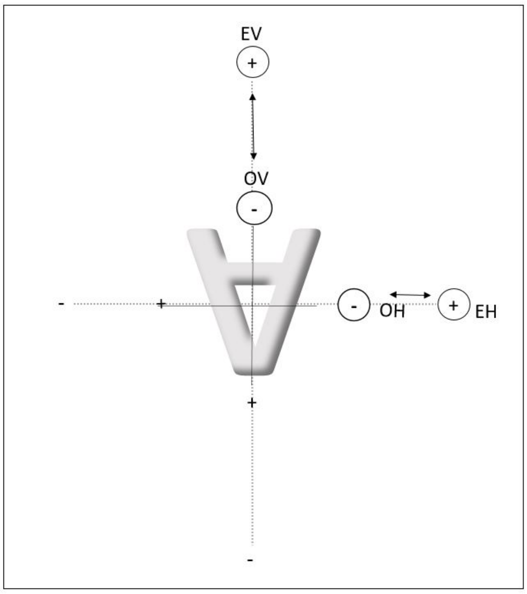
This hypothesis was also tested empirically. Gregory and McCloskey (2010) observed in a series of their own experiments that confusions across the vertical object axis were more common than confusions across the horizontal object axis. However, as all of the objects which they used in their experiments were asymmetric across both the object's vertical and horizontal mirror axis, the authors suspected that the observed types of mirror-confusions could also be influenced by the salience of the object's features. The reason for this was that in most of their objects, the features differentiating the two sides of the object's vertical axis seemed to be more salient than the features differentiating the object's horizontal axis as shown in Figure 1.4 (a). Thus, Gregory and McCloskey conducted another experiment in which they created a series of stimulus objects which were each based on a combination different of features (e.g., a square, a wedge, a pentagon, a half circle). Importantly, they manipulated the salience of features differentiating the sides of the objects. Stimuli could either be neutral (salience of features equally pronounced across both mirror axes), or with the salience of features being more pronounced across the vertical mirror axis, or with the salience of their features more pronounced across the horizontal mirror axis. After a single stimulus object was displayed on a screen, participants were asked to report the orientation of the picture on an alternative forced-choice array. Results showed that the relative overall frequency of errors induced by mirroring across the objects vertical and horizontal axis did not differ, indicating that the salience of object features had an impact on the type of mirror-confusions which participants had produced. Objects in which salience of features was more pronounced across the vertical axis, produced more confusions across the vertical axis. By contrast, objects in which feature salience was more pronounced across the horizontal axis, produced more confusions across the horizontal axis. This finding is particularly relevant for the confusion of the lower-case letters of the Latin Alphabet as they are usually asymmetrical across both their vertical and the horizontal axis and the salience of the letter's features is often more pronounced either across the vertical mirror axis as exemplified in Figure 1.4 (a) and (b) or across the horizontal axis as exemplified in Figure 1.4 (c) and (d).



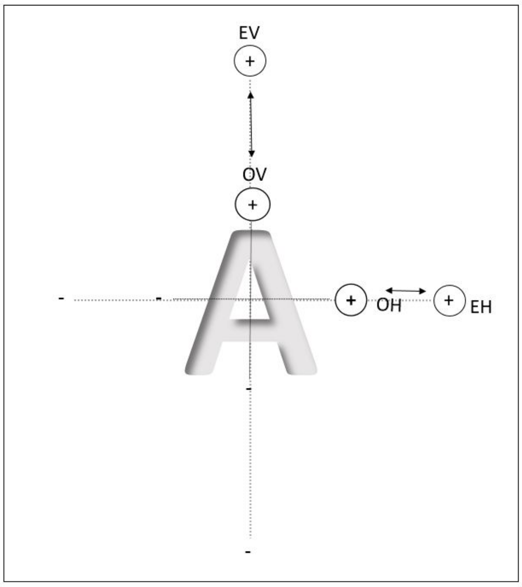
(a) 45 ° tilt



(b) Upright position



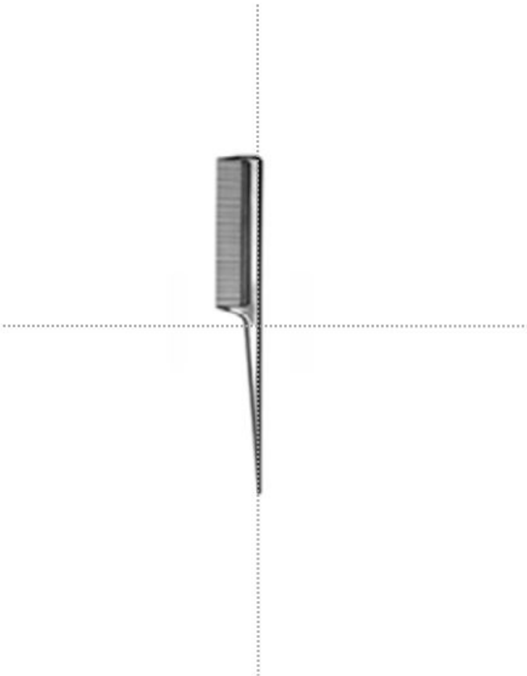
(c) Horizontal mirroring



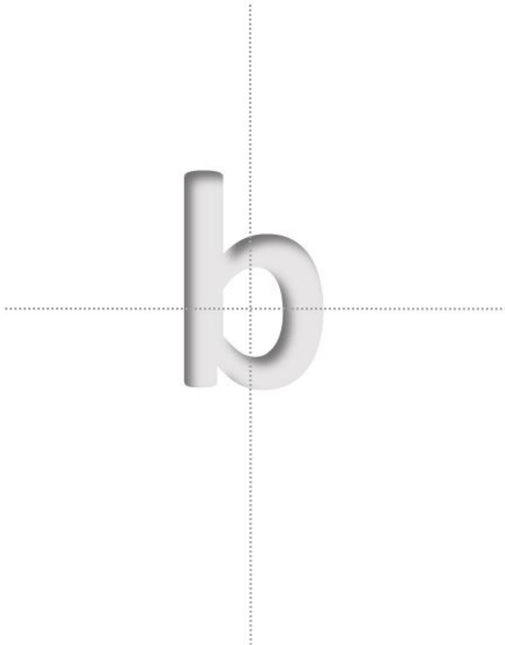
(d) Vertical mirroring

FIGURE 1.3: a-d: Representing polarity correspondences between object and extrinsic axes according to McCloskey et al. (2006); McCloskey (2009). OV = object's vertical axis, OH = object's horizontal axis, EV = external vertical axis, EH = external horizontal axis

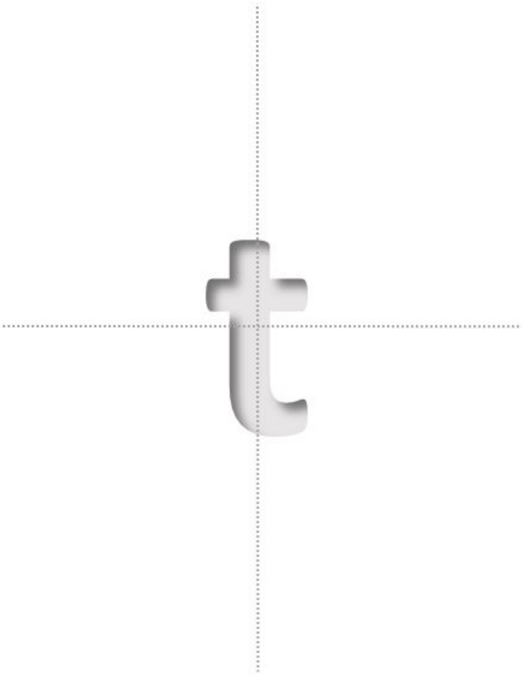
Note: Adapted from Gregory and McCloskey (2010)



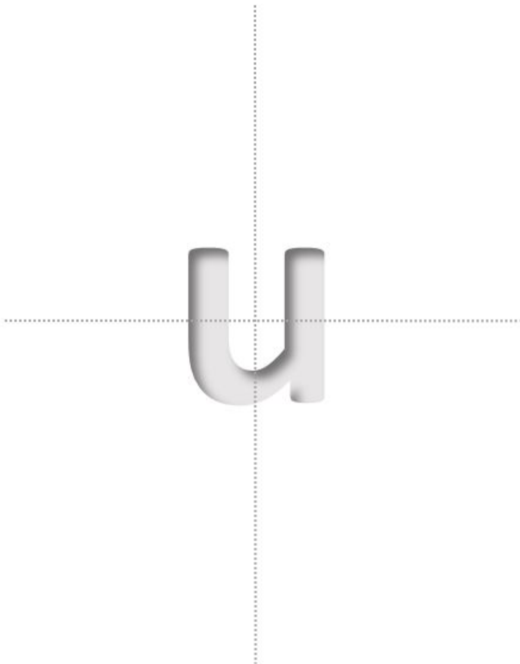
(a) Feature salience OV > OH



(b) Feature salience OV > OH



(c) Feature salience OH > OV



(d) Feature salience OH > OV

FIGURE 1.4: a-d: Examples of feature salience differentiating the sides of visual objects around their vertical and horizontal mirror axes. OV = object's vertical axis, OH = object's horizontal axis.

Note: Figure 1.3 (a) adapted from Gregory and McCloskey (2010).

1.1.3 Mirror-confusions in Native Readers of Different Scripts

On the one hand, the properties of different writing systems have evolved to fit basic constraints of the human visual system (Dehaene et al., 2010; Changizi et al., 2006). On the other hand, the plasticity of the cognitive system enables humans to efficiently adapt to a changing social and cultural environment. As writing systems are made by humans and their purpose is to be read by them, it is not surprising that letter shapes tend to reproduce patterns found in the external world (Changizi et al., 2006) in order to facilitate their recognition. However, the relationship between human cognition and writings systems is not unidirectional. Rather, the relationship is reciprocal in that the cognitive processing of text also adapts to the characteristics of a particular writing system as represented in Figure 1.5.

The modern Latin alphabet comprises several letters which are susceptible to mirror-confusions because they have an exact or very similar mirror image counterpart (i.e., b-d, q-p, p-b, q-d, n-u, W-M, t-f). By contrast, there are other writing systems such as Tamil which do not comprise letters that are susceptible to such mirror-confusions. One way to corroborate empirically whether the cognitive processing of written language adapts to the peculiarities of a writing-system is by comparing specific cognitive abilities related to reading in literate and illiterate adults who speak the same language. Alternatively, one can compare literates of distinct languages and writing systems which differ with regard to one characteristic: whether they comprise letters which are susceptible to mirror-confusions or not.

For example, Kolinsky et al. (2011) isolated in a mirror-image discrimination task the effect of literacy acquisition in the Latin alphabetical writing system on the ability to discriminate mirror-images. In their experiments, illiterate adults as well readers of the Latin alphabet that were either ex-illiterate or schooled literate adults were asked to distinguish enantiomorphs, a pair of mirror-images of a visual shape. Illiterate participants displayed much poorer performance than both ex-illiterate schooled literate individuals, indicating that pre-literate adults have a tendency to mirror-generalize visual input whereas literate adults do not.

In a more recent study, Fernandes et al. (2021) compared the ability to discriminate mirror-images of letters in readers of two different writing systems: The alphabetical writing system and Tamil, the latter not containing reversible letters. Illiterates, monolingual Tamil literates and Tamil-English bilinguals performed a speeded same-different match task in which letters had to be distinguished based on orientation or judged the same based on their shape. Participants saw both reversible and non-reversible letters which were vertically mirrored (i.e. b vs. d) and rotated clockwise by 180° (i.e. b vs. q). The 180° rotation was included as a control condition because according to the authors, by contrast to vertical mirroring, the 180° rotation does not mimic mirror-generalization. Results showed that only Tamil-English bilinguals exhibited (task- irrelevant) *automatic* mirror-image discrimination: when comparing performance in shape based judgments for mirrored versus normally presented letters, bilinguals revealed a mirror-processing cost for reversible compared to non-reversible letters whereas monolingual Tamil speakers did not. Furthermore, compared to Tamil speakers, bilinguals revealed a reduced disadvantage on orientation- over shape based judgment for mirrored but not rotated letters (but see Danziger & Pederson, 1998; Pederson, 2003, for evidence against the mirror-processing cost in Tamil), indicating that automatic, unconscious mirror-image discrimination emerges as a mechanism of adaptation to a writing system which comprises confusable letters.

In summary, the aforedescribed studies provide evidence that the relationship between human cognition and the characteristics of a particular writing system is reciprocal rather than unidirectional. On the one hand, writing systems have been designed to fit humans' basic cognitive constraints. On the other hand, the properties of a writing system seem to shape the cognitive mechanisms that underlie the reading process. In particular, general visual principles of mirror-generalization seem to be suppressed or inhibited as a result of reading experience in scripts which comprise reversible letters. But do readers of the alphabetical writing system really completely loose the tendency to mirror-confuse letters once they have become efficient readers? Or do adult readers still unconsciously mirror letters within words during an early, automatic stage of word recognition process? This question will be addressed in the following chapter.

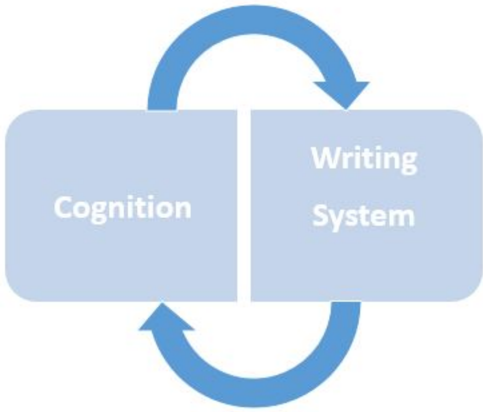


FIGURE 1.5: Schematic representation of the reciprocal relationship between a writing system and cognitive processes in reading.

1.2 Early, Automatic Mirror-image Reversals in Adult Readers

Interestingly, involuntary mirror-confusions of letters have also been observed in illiterate adults (Pegado et al., 2014b; Fernandes et al., 2021) and - at an early and automatic processing stage - even in functional reading adults (Soares et al., 2021, 2019; Perea et al., 2011). Predictions on such early, automatic processes during visual word recognition can be made based on data from a masked priming experiment. In masked priming, a procedure developed by Forster and Davis (1984), participants are presented very briefly (i.e. 50 ms) with a prime which is followed by a target. The prime is presented too briefly to be consciously perceived by the reader. It is well established that a prime can affect the processing of the target and that, depending on the prime's characteristics, effects can either be inhibiting or facilitating to the recognition of the target. An identical prime and target (e.g., table-TABLE), for instance, is referred to as an identity prime which is known to facilitate target word recognition when compared to a control condition. Identity priming effects are thought to occur because the unconscious perception of the prime pre-activates in the reader's mental lexicon the corresponding target word and, thus, the time required to process the target word decreases. In an orthographic masked mirror-priming paradigm, a mirror-priming condition is created by using an identity prime in which individual letters are mirrored (i.e. lɘɒf - LEAF). If letters are processed irrespectively of their left-right orientation, then vertically mirrored letters should be processed like a simple allographs of the upright letter and produce priming effects on word recognition that are similar or equal to the identity priming effect. However, if a mirror-prime comprises a reversible letter (e.g. tadle - TABLE) which pre-activates two competing letter representations (i.e. b activates b and d), then such a mirror-prime could also produce inhibitory effects on target word recognition. Previous studies which have used an orthographic masked mirror-priming paradigm have found both priming (and thus facilitating) and inhibitory effects of mirror-primes on visual word recognition in adults.

1.2.1 Mirror-priming effects for Words with Non-Reversible Letters

Mirror-priming studies suggest that the perception of mirrored letters and words activates the correct letter or word representation because, as suggested by Corballis and Roldan (1974), visual input is encoded together with its vertical mirror-image reversal. To test this hypothesis, Duñabeitia et al. (2011) used primes with vertically mirrored letters and entirely mirrored words in a go/no go semantic categorization task. In a first experiment, targets were preceded by either an identity prime (e.g. operación), a control prime or a mirror-prime. The mirror-prime consisted of a word in which internal letters were vertically mirrored (e.g. opɘɿɒɔión) while initial and final letters were presented normally. In the control condition, the critical letters were replaced by other mirrored letters (e.g. opɒɔɘɿión). In a second experiment, Duñabeitia and colleagues used vertically mirrored words rather than words with individually mirrored letters. Using Event Related Potentials (ERPs), they showed that at early stages of processing, words which comprised vertically mirrored letters and entirely mirrored words produced early electrophysiological brain responses (N250 component) on target word recognition that did not differ significantly from the effects evoked by the identity primes. According to the authors, their results can be taken as evidence that vertical mirror-primes are processed like an identity prime during an early, automatic and unconscious stage of the word recognition process. By obtaining the same pattern of results for primes comprising mirrored letters and entirely mirrored primes the authors demonstrated that the observed mirror priming effects were independent of visual similarity. On a behavioural level, Winskel and Perea (2018) showed in a masked priming same-different match task with 4-letter words in which 2 internal letters of the prime were mirrored, that native English readers revealed mirror-priming effects for mirror-primes with non-reversible letters. However, these priming effects were less pronounced than the identity priming effect. When Winskel and Perea repeated the experiment with native readers of Thai and in Thai language (which does not comprise reversible letters), they found that mirror-priming effects were as pronounced as the identity priming effects. In a more recent study and in line with Winskel and Perea, Brossette et al. (2022) found that in a lexical decision task combined with a sandwich-masked priming paradigm, that primes which were entirely written in vertically mirrored letters, produced priming effects on target word recognition. Again, these priming effects were not as pronounced as the identity priming effects. By contrast, when conducting the same experiment with a conventional masked priming paradigm, Brossette and colleagues found no mirror-priming effects. The authors argued that a lexical decision task combined with a conventional masked priming paradigm may not be sensitive enough to capture mirror-priming effects on a behavioural level. Furthermore, the authors also found that mirror-priming effects were graded by the prime-target visual overlap and concluded that this could be due to either of two things: the initial prime in the sandwich procedure could have pre-activated a whole-word representation which, in turn, could have reinforced the influence of a regularization process. Such a regularization process has previously been observed for primes which contained letter-like numbers (e.g. in M4T3R14L, "1" regularized as "I"). Alternatively, the graded mirror-priming effects could have been due to the redundancy between mirror letters and their canonical format which might have led to a partial activation of the feature detector for the canonical letter and, in turn, activate the higher-level abstract letter representations.

1.2.2 Inhibitory Effects for Words with Reversible Letters

Other mirror-priming studies have provided evidence for inhibitory effects of mirror-primes if the primes comprise reversible letters. For example, Perea et al. (2011)

used a masked mirror priming paradigm with a lexical decision task to compare the recognition of target words which either comprised reversible (and thus confusable) letters (e.g., idea - IDEA) or only non-reversible letters (e.g., arena - ARENA). In the prime, critical letters were either identical, mirrored or an unrelated control-letter. Perea et al. (2011) could show that the recognition of the target words with reversible letters was significantly slower when the prime's critical letter was mirrored (danana - BANANA) as compared to the condition with an unrelated control-letter (tatana - BANANA). This interference did not occur for words with non-reversible letters. The results of Perea and colleagues thus suggest that in functional reading adults, only words which comprise confusable letters produce mirror interference effects on early, automatic processes in visual word recognition whereas non-reversible letters do not.

Similar to the study conducted by Perea and colleagues, Soares et al. (2019) conducted a lexical decision (go/no-go) masked priming experiment with skilled adult readers, intermediate readers (fifth-grade children) and beginning readers (3rd grade readers). Soares and colleagues used also reversible letters but additionally manipulated the orientation of reversible letters. The rationale behind their orientation manipulation is the assumption that readers implicitly learn that most letters face right (e.g. b, r, k, p, l) rather than left (e.g. d, j) and that this should lead to mirror-interference effects for words which comprise the letter "d" (d-words) but not for words which comprise the letter "b" (b-words). Furthermore, unlike Perea et al. (2011), Soares and colleagues presented the primes and the targets in lowercase letters because the letter "d" changes its orientation when capitalized (i.e., d->D), whereas the letter "b" does not (b->B). The researchers found reliable mirror-interference effects for d-words but not for b-words in skilled adult readers and in intermediate readers (5th graders). By contrast, no mirror-interference effects were found for beginning readers (3rd graders). Their results indicate that 1) reading experience drives the suppression or unlearning of mirror-generalization and, 2) mirror-interference effects are not merely driven by the presence of a reversible letter but they also depend on the letter's orientation. In a later experiment, Soares et al. (2021) could show that mirror-interference effects induced by letter orientation occur also for non-reversible letters.

1.2.3 Mirror-priming Effects and Models of Visual Word Recognition

The process of recognizing words as visual objects is one of the central aspects of reading and thus, it is one of the central aspects addressed by contemporary models of visual word recognition (Norris, 2013). One of the challenges which all of these models face is how readers achieve translational and/or mirror-invariance (Perea et al., 2011) which, applied to letter recognition, means the ability to recognize " ɒ " and " ɐ " as instances (or allographs) of the letter "a" or "A". Until the present, these early orthographic processes during visual word recognition are not entirely understood. In hierarchical models of letter and word recognition (Dehaene et al., 2005), invariant word recognition is achieved through letter detectors. Visual letter-features are combined by shape-specific and thus case-specific letter detectors (i.e. "a" and *a*", but not "A" activate the letter "a"). These letter detectors in turn can activate abstract letter representations which are case-insensitive (i.e. "a" and *a*" and "A" all activate the abstract letter representation "a/A") which, in turn, drives lexical access. There are two theoretical frameworks which can explain priming effects in visual word recognition.

Mirror-Priming Effects in the Activation Framework The *activation* framework assumes that words are presented as nodes in a network and once a node reaches a certain threshold, the node is activated and lexical access takes place (i.e. the word is recognized). The concept of activation was initially formalized in the Interactive Activation Model (IAM) by McClelland and Rumelhart (1981) and Rumelhart and McClelland (1982) (see Figure 1.6) and is still a basic premise in many other models of visual word recognition (Kinoshita, 2015). According to the activation framework, priming effects in a lexical decision task are determined by the pre-activation that a prime produces of a word which has a whole-word orthographic representation in the reader's mental lexicon. This assumption leads to the prediction that words but not non-words should because non-words have no whole-word orthographic representation in the mental lexicon.

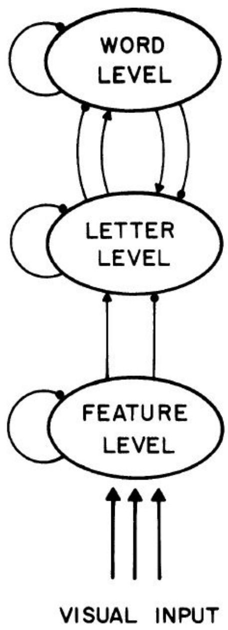


FIGURE 1.6: Schematic representation of the IAM (Rumelhart & McClelland, 1982)

In the IAM, the word node receives connections from the letter units and vice-versa. The connections between the word and the letter-level can either be inhibiting or activating in both directions. The letter units receive connections from the feature units that can either be inhibiting or activating. The letter units are activated when the perceived features are compatible with the abstract letter representation and they are inhibited if the perceived features are not compatible with the abstract letter-representation. In the IAM, there is no inhibitory feedback from the letter to the feature level.

If letters are generalized to their vertical mirror-image, then " ɿ " should immediately activate the abstract orthographic letter representation "r/R". If letters are also generalized to their horizontal mirror-image, then the response to " ɹ " should be very similar. Hence, mirror-primes should boost the activation of a word almost as strong as normally presented letters if letters are unconsciously mirror-reversed during an early, automatic stage of the word recognition process. Furthermore, the IAM would predict mirror-priming effects on words but not on non-words because the concept of pre-activation of a whole-word orthographic representation in the mental lexicon can only apply to items which have a lexical representation. As non-words do not have a lexical representation, priming effects are not predicted to occur on non-words in this model.

Mirror-Priming Effects in the Bayesian Reader Model Alternatively, the *Bayesian Reader Model*, proposed by Norris (2006), Norris and Kinoshita (2008) and Norris and Kinoshita (2012), assumes that the reader integrates information through the computation of conditional probabilities based on Bayes theorem, and the output of this computation is the likelihood of a specific hypothesis, given the evidence. Bayes theorem is given by equation:

$$P(H|E) = \frac{P(H) \times P(E|H)}{\sum_{i=n}^{i=0} P(H_i) \times P(E|H_i)}$$

where P(H) is the prior knowledge of the likelihood (a-priori probability) with which an event or a hypothesis (H) occurs, (E) is the evidence (i.e. the perceived perceptual input) which is taken into account to recompute the likelihood of (H), $P(H_i)$ corresponds to the prior probabilities of the possible hypotheses and $P(E|H_i)$ is the likelihood that the evidence is consistent with each of the hypotheses given by $P(H_i)$.

In reading, the hypothesis is a given word and the evidence is the perceptual data or the input which the reader perceives. $P(H)$ quantifies the probability of the hypothesis being true before knowing the evidence. Thus, in the case of reading, $P(H)$ corresponds to a word's frequency of occurrence (i.e. whether a word is common or rather uncommon in everyday use) or, when words are presented in a sentence, the word's predictability given its broader linguistic context. In this framework, the probability of each word is a function of the evidence for this word divided by the evidence for all other words:

$$P(Word_x|Input) = \frac{P(Word_x) \times P(Input|Word_x)}{\sum_{i=n}^{i=0} P(Word_i) \times P(Input|Word_i)}$$

In the Bayesian Reader Model, masked priming effects are not explained in terms of a pre-activation of the target word in the reader's mental lexicon. Rather, the unconscious perception of the prime makes a word more or less predictable. According to Norris and Kinoshita (2008) this is because the perceptual system is tricked into processing the prime and the target as a single object and as a consequence, the prime changes the a-priori probabilities of the target word. To put it in words of Norris and Kinoshita (2008), in a priming paradigm both the prime and the target could be combined to provide support for the hypothesis that the input contains the case-independent abstract letter representation "a/A" if the prime contains the lower-case letter "a" and the target contains the upper-case letter "A". Or, both the prime and the target could provide evidence for words containing the letter "a/A" in the appropriate position. In a lexical decision task, to give a "yes" answer, the model does not have to identify which word was perceived. Neither is the identification of individual letters with a high degree of certainty required. Rather, the model determines that it is unlikely that the input came from a word. The Bayesian reader also makes the novel prediction that by changing the task, masked priming effects generalize to non-words. For example, by contrast to the lexical decision task, the same-different match task, requires participants to decide whether a reference and a target are the same or whether they are different. References and targets can be letter strings which form either words or non-words. By contrast to the lexical decision task, the same-different match task has been shown to produce equally robust priming effects for word and non-word targets in the *Same* condition whereas it does not show effects in the *Different* condition (Norris and Kinoshita, 2008; Kinoshita & Norris, 2009).

In summary, for the lexical decision task, both the IAM and the Bayesian framework predict effects on words but not on non-words. However, the Bayesian framework also makes the novel prediction that by using a same-different match task instead of a lexical decision task, masked priming effects should generalize to non-words (Kinoshita & Norris, 2009). Effects on non-words can be taken as an indicator that the nature of the observed priming effects is pre-lexical. Until the present, however, mirror-priming effects have only been observed for words or in tasks which require lexical activation and thus, it remains unknown whether the locus of the mirror-priming effect is lexical or pre-lexical. Furthermore, we do not know whether mirror-priming effects are moderated by the letters confusability. This is plausible because it has been shown that mirror-priming effects can vary depending on whether primes comprise reversible or non-reversible letters. Such inhibitory effects may also occur for other letters which are not reversible but which increase inter-letter-similarity when mirrored. Moreover, previous masked mirror-priming studies have merely examined mirror-priming effects for primes comprising vertically mirrored letters. It thus remains unknown whether implicit mirror-image reversals in adults also occur across the horizontal axis.

While mirror-priming studies focus on the early, automatic and unconscious processes in visual word recognition, there are other paradigms which have examined the impact of mirroring letters on later stages of the reading process. In these experiments, adults are asked to read text which is subjected to different mirror-transformations. The rationale behind this is that different mirror-transformations of text affect different aspects of the spatial configurations of letters and words and thus, these mirror-reading tasks have previously been used to study the perceptual processes of ordinary reading. However, these studies can also provide some first insights on how mirror-confusions impact the reading process in adults.

1.3 Effects of Mirror-image Reversals on Reading in Adults

1.3.1 The Impact of Mirror-image Reversals on Word Recognition and Eye-movements

As skilled adult readers are very efficient at identifying the letters of the Latin alphabet, mirror-confusions can be induced by applying different mirror-transformations to letters or entire text. These transformations include the mirroring of individual letters or mirroring entire words. For example, Poldrack et al. (1998) used a mirror-reading task to study the process of perceptual skill acquisition in reading in a training study in which participants learned over several training sessions to read mirrored text. In all sessions, participants performed a lexical decision task in which entire words were either vertically mirrored (mirror-condition) or presented normally (baseline-condition). After a first fMRI scan and a following training period which lasted three further training sessions, participants returned for a second scan session in which the pattern of brain activation during mirror-reading compared to normal reading for both previously trained and untrained words was measured. Results showed that mirror-reading involved an increased activation in the left fusiform gyrus with training, a brain region which (together with the extrastriate cortex) is activated in letter processing compared to the processing of false fonts (Price et al., 1996). Thus, the results indicate that on a neuronal level, mirror-reading involves an increased involvement of letter recognition processing (Poldrack et al., 1998).

Similarly, Björnström et al. (2014) compared reading processes for words that were presented in different mirror transformations on a behavioural level. As in the experiment of Poldrack and colleagues, the mirror-transformations were applied to the entire word rather than the individual component letters. The participants' task was to read the word out loud as soon as they had identified it as a whole. Poldrack and colleagues used a 2(upright condition vs 180° rotation) by 3(normal vs vertical mirroring vs backwards spelled) design. Word-length was also manipulated because length-effects (i.e. the observation that long words are read slower than short words) are a marker of sublexical, letter-by-letter decoding as opposed to the more efficient whole word recognition or direct lexical activation. Their results showed that upright text revealed smaller word length effects than 180° rotated text and that vertically mirrored text revealed larger word length effects than backward text, indicating that in mirror-reading, readers use primarily local letters rather than global word form.

Turning to the effect of different mirror-transformations on global sentence reading, Kolers (1968) conducted a study in which participants read aloud sentences in which text was presented normally, mirrored horizontally, rotated 180° or mirrored vertically. Furthermore individual letters were either presented normally, vertically mirrored horizontally mirrored or rotated 180°. Kolers found that the difference between mirror-conditions was mainly driven by an interaction of the reading direction and the direction the letters faced, both of which varied across the transformation conditions he used. Most importantly for the current issue, the results showed that when only letters were mirrored and the reading direction was from left to right, vertical mirroring was less disruptive than horizontal mirroring. This was revealed by the word reading rate (words per minute), which, compared to the normal condition, decreased by approximately 54% in the vertical mirror-condition and by approximately 77% in the horizontal mirror-condition.

Turning to the impact of mirror-image reversals on eye-movements, previous studies are rather scarce and they have mainly focused on saccade programming or the eye's landing position. For example, Kowler and Anton (1987) investigated how the quality of saccadic skill impacts the acquisition of visual information during a reading task. Participants read texts in different mirror-transformation conditions, including text that was presented with individual letters either horizontally or vertically mirrored. Focusing on the results with individually mirrored letters, they found that reading times increased substantially from ca. 60 ms/letter during normal reading to ca. 240 ms/letter in the vertical mirror-condition and ca. 460 ms/letter in the horizontal mirror-condition. As the authors were mainly interested in the effects of mirroring on saccade programming, word reading times were not analysed. However, the authors reported that mean saccade length was much smaller during the reading of mirrored text, indicating that words were decoded serially and less fluently.

Recently, Chandra et al. (2020) investigated how the reading of mirrored text impacted participants' oculomotor processes and the eyes' landing positions. In their study, participants read texts in a normal reading condition and in a condition in which individual letters and/or the entire words were vertically mirrored. Just focusing on the mirror-letter condition, Chandra and colleagues reported that mirroring increased mean the fixation duration from ca. 250 ms to ca. 300 ms. Furthermore, skipping probability decreased from from 30 to 13% and regressive saccades decreased from 12 to 7%.

In sum, we know from previous research that mirror-reading leads the readers to switch to a more attention demanding, sublexical decoding strategy which involves more effortful, serial, letter-by-letter decoding as revealed by an increase in word-length effects. Unfortunately, previous studies in which mirrored text has been used did not consider that word reading times may have varied depending on whether a word comprises confusable letters. However, this is plausible because a word might be more or less confusable depending on its proportion of reversible (e.g. b vs d or b vs p), confusable (e.g. e vs ɘ) and symmetrical (e.g. o, x, H) letters. To address this question, however, the word's overall propensity to be confused when mirrored (i.e. the word's mirror-confusability) needs to be quantified and manipulated in a controlled experimental setting and reading times need to be analysed on the word-level.

Word reading times reflects the ease with which readers can process text (Liversedge & Findlay, 2000; Rayner, 2009; Rayner, 1998). Tracking the readers' eye movements on the word-level when reading text with mirrored letters has the potential to provide a fine-grained online protocol of how the mirror-reading process unfolds in time.

1.3.2 Mirror-image Reversals and Eye-movements in Reading

While mirroring letters is a visual manipulation that slows down the reading process substantially, there are also more subtle visual manipulations such as contrast reduction or blurring (Staub, 2020) which have been shown to affect the reading process. Furthermore, there are linguistic variables such as word frequency and predictability which can affect word reading times. For example, it is well established that frequent words receive shorter fixations and have a higher skipping probability (Inhoff & Rayner, 1986; Kliegl et al., 2006; Rayner & Duffy, 1986) and that words which have a low predictability given their preceding context receive longer reading times (Altarriba et al., 1996; Balota et al., 1985; Rayner et al., 2004).

The relationship between effects of a visual and a linguistic variable on eye-movement behaviour is highly relevant for the development of models of eye-movement control during reading. While we know that both linguistic and visual variables can affect eye-movement behaviour during the reading of connected text (Liversedge & Findlay, 2000; Rayner, 2009; Rayner, 1998), it is unclear whether visual and linguistic variables produce additive or interactive effects on eye-movements.

According the additive factors logic of Sternberg (1969), two variables which produce additive effects exert an impact on different processing stages, whereas two variables which produce interactive effects may affect at least impact one common stage of processing. Although it is important to note that models of eye-movement control do not directly address this issue (Staub, 2020), the additive factors logic can also be applied to the relationship between visual and linguistic variables on eye-movements during reading.

For example, the E-Z reader model (Reichle et al., 2012) assumes an early stage of lexical processing, L1, which includes the extraction and identification of the orthographic form of the word. This stage strictly precedes a later lexical processing stage, L2, which is solely involved with processing at the phonological and semantic level. Such a processing architecture would imply that mirroring, as a visual manipulation, targets orthographic form processing (i.e. the processing of letters) and produces additive effects with a linguistic variable such as word frequency as represented in Figure 1.1 A. Alternatively, an interactive pattern of a visual and a linguistic variable would indicate that processing is not staged but rather cascaded across levels. When processing is cascaded, partial activation at one level has an immediate impact on units at a later level (Coltheart et al., 2001) as represented in Figure 1.1 B.

The empirical picture regarding the question whether visual and linguistic variables produce additive or interactive effects on eye-movements is mixed. Studies in which stimulus quality was manipulated via contrast reduction or blurring found additive effects (Staub, 2020) whereas other manipulations such as font difficulty (Staub, 2020; Slattery & Rayner, 2010), (but see Rayner et al., 2006), letter rotation (Blythe et al., 2019), or case alternation (Reingold et al., 2010), which target the letter-level of processing, found interactive effects with word frequency. Until the present, it remains unknown whether mirroring letters and word-frequency are two variable which produce additive or interactive effects on eye-movement behaviour. Answering this question could shed a light on the time-course of mirror-interference effects during reading.

1.4 Research Questions

The introduction so far has shown that the origins of mirror-confusions in reading have been proposed to be rooted in general visual principles mirror-image generalization (Bornstein et al., 1978; Logothetis & Pauls, 1995; Rollenhagen & Olson, 2000),

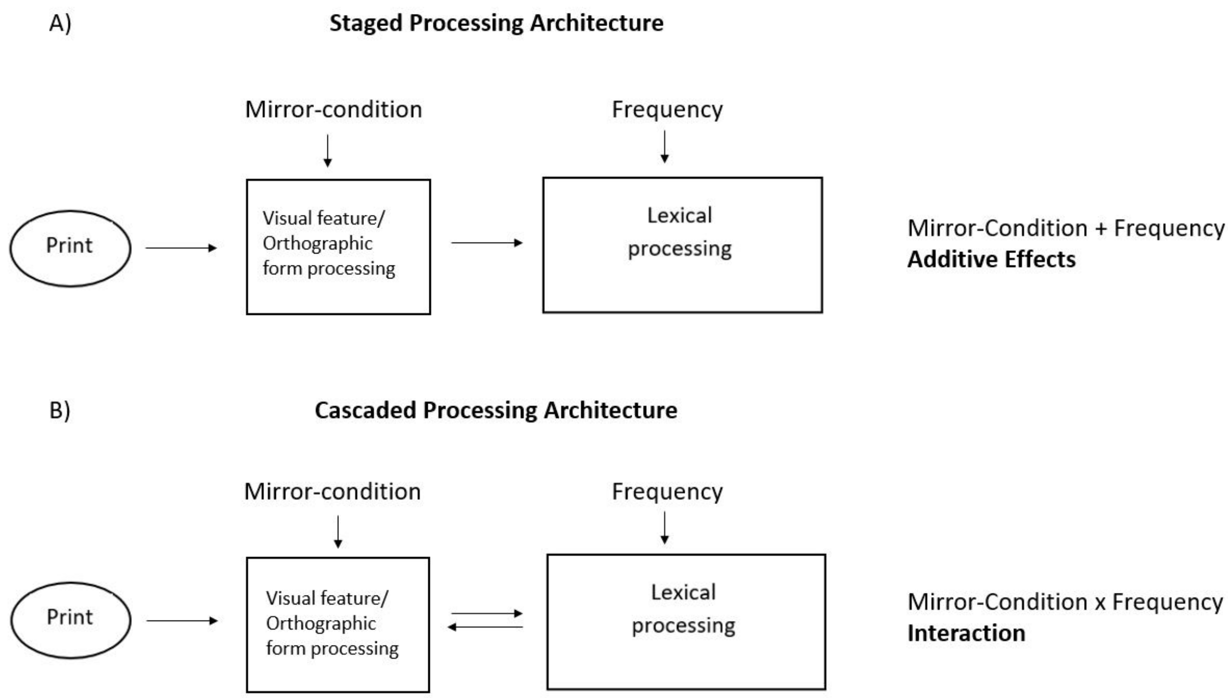


FIGURE 1.7: Schematic representation of additive and interactive effects of Mirroring and Frequency on processing.

symmetry generalization (Lachmann, 2002; Lachmann & van Leeuwen, 2014) or mirror-invariance (Dehaene et al., 2010, 2015) and that these confusions keep affecting the reading process in functional reading adults (Duñabeitia et al., 2011; Perea et al., 2011; Soares et al., 2019). The exact nature and locus of mirror-effects in adults, however, remains largely undisclosed. In particular, it remains unknown whether involuntary mirror-confusions generalize to confusions across the horizontal axis, whether their locus is lexical or pre-lexical and whether the *mirror-confusability* of words has an impact in visual word recognition.

In line with Dehaene et al. (2010), Corballis and Beale (1976), Bornstein, Gross, and Wolf (1978), Logothetis and Pauls (1995) and Rollenhagen and Olson (2000), previous research on involuntary mirror-image confusions in functional reading adults has particularly focused on vertical confusions, although it has been argued that mirror-generalization also occurs across the horizontal axis (Lachmann, 2002; McCloskey M., Valtonen J., & Cohen Sherman J., 2006; McCloskey, 2009; Gregory & McCloskey, 2010). Furthermore, previous mirror-priming studies so far have only used tasks which involve lexical activation such as a semantic categorization task (Duñabeitia et al., 2011) or they have used a same-different match task but only with words (Winskel & Perea, 2018). These tasks do not allow to draw conclusions on whether the locus of mirror priming effects is lexical or pre-lexical by nature because both tasks involve lexical activation. In order to understand the nature and locus of mirror-priming effects, studies need to implement mirror-priming paradigms which do not involve lexical activation (e.g. a same-different match task including both words and non-words) and they also need to include a horizontal mirror-priming condition (i.e. in which letters within primes are mirrored horizontally). Addressing these questions can provide an evidentiary basis for theories on mirror-confusions in reading which make different predictions on whether involuntary letter reversals are confined to vertical confusions or whether they also generalize to confusions across the horizontal axis. Furthermore, understanding the exact temporal locus of mirror-priming in reading advances our understanding of the cognitive mechanisms that underlie mirror-confusions in reading.

Previous research on mirror-interference effects in reading has either examined the impact of reversible compared to non-reversible letters on the early, automatic stage of the word recognition process (Soares et al., 2019; Perea et al., 2011), or they have tracked the eye-movements of adults readers while reading entirely mirrored sentences (Chandra et al., 2020; Kowler & Anton, 1987). In order to gain a more refined picture of mirror- interference effects in reading, however, a systematic examination of the Latin alphabet's mirror-confusability and a quantification of the average mirror-confusability of words is required. Examining the nature of mirror-interference effects can provide insights on if and how the visual system interacts with the sensitivity of a script to mirror reversals. Examining if and how the mirror-confusability of words affects reading processes in adults has the potential to inform models visual word recognition and eye-movement control in reading which, until the present, do not consider a word's *mirror-confusability* to be a visual variable that has an impact on the ease with which words can be recognized.

Furthermore, the time-course of mirror-interference effects during reading remains largely unknown. The reason for this is that previous studies which have examined the impact of mirroring letters on eye-movements have merely analysed global eye-movement measures on the sentence level (Chandra et al., 2020; Kowler & Anton, 1987) and they have not combined mirroring with a linguistic variable such as word frequency. In order to make inferences on when, over the course of word recognition, a visual variable moderates word reading times, it is necessary to combine the visual manipulation with a linguistic manipulation on the word level. If the properties of the text such as mirroring letters influence language related processes (word recognition itself), this suggest that a word may be matched against items in the mental orthographic lexicon, by way of hypotheses or guesses, before individual letters have been identified (cascaded processing). If, by contrast, effects of mirroring text are confined to early, orthographic processes, this would suggest that word recognition happens only after individual letters are identified (staged or thresholded processing).

This research project addresses the question of *if*, *how* and *when* mirroring letters affects the reading process in functional reading adults. The question of *how* will be addressed by including both vertically and horizontally mirrored letters across all studies. Furthermore, mirror-interference effects will be examined by systematically quantifying a word's mirror-confusability. The question of *when* will be addressed by using a multi-method approach which allows each study to tap into a different stage of the word recognition process ranging from:

1. the earliest, automatic and unconscious processes in visual word recognition
2. the early, orthographic processes which involve the visual processing of letters
3. later, language related processes which correspond to word recognition itself (lexical processes)

1.5 Study Overview

In the above section I outlined some of the unresolved questions that arise from the gaps in the research literature at present. In order to address these questions, three studies with a varying methodological approach were undertaken. Study 1 used a masked priming paradigm to examine vertical and horizontal mirror-priming effects during the early, automatic and pre-lexical stages of the word recognition process and it examined whether these effects vary with a word's mirror-confusability. Study 2 used a silent reading tasked combined with eye-tracking to tap into the early stages of lexical processing by examining whether mirror-interference effects are confided to early orthographic processes or whether these confusions also affect lexical stages of the reading process. Study 3 used a lexical decision task and a silent sentence reading task with eye-tracking to examine whether mirror-interference effects on lexical processes vary with a word's mirror-confusability.

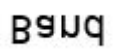
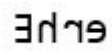
1.5.1 Study 1

Study 1 addresses the question *if* and *when* early, automatic mirror-image reversals occur during word recognition in adult readers. Duñabeitia et al. (2011) could show that words which comprise vertically mirrored *non-reversible* letters and words which are entirely vertically mirrored produce the same early electrophysiological brain responses on target word recognition as the identity prime. Other masked mirror-priming studies have shown that these mirror-priming effects do not generalize to primes with *reversible* letters (Perea et al., 2011; Soares et al., 2019). The exact nature and locus of mirror-priming effect remains largely unknown for several reasons. First, because the reported studies have used tasks which require lexical activation (e.g. semantic categorization, lexical decision or same-different match task with words) and which therefore do not allow to tap into pre-lexical stages of the word recognition process. Second, because previous studies have been limited to examining vertical but not horizontal mirror-priming effects. It has been argued that automatic mirror-image reversals are rooted in mirror-generalization which entails the processing of *vertical* mirror-images (Dehaene et al., 2005; Corballis & Beale, 1976; Bornstein et al., 1978; Logothetis & Pauls, 1995; Rollenhagen & Olson, 2000), but evidence suggest that mirror-image generalization also occurs occurs across the *horizontal* axis (McCloskey M., Valtonen J. & Cohen Sherman J., 2006; McCloskey, 2009; Gregory & McCloskey, 2010; Lachmann, 2002). If the latter was true, then both vertically and horizontally mirrored letters within primes should be (mis)identified as the correct letters and produce priming effects on target word recognition. Study 1 thus extends previous research in that it examines 1) whether implicit mirror-image reversals during the early, automatic stages of word recognition occur both vertically and horizontally, 2) whether mirror-priming effects are pre-lexical by nature and 3) whether mirror-priming effects are moderated by the proportion of reversible, confusable and symmetrical letters within the prime. Two masked mirror-priming experiments are conducted whereby the same set of stimulus material is used in the two experiments. In the first experiment, a lexical decision task is used whereas in a second experiment, a cross-case same-different match task including both words and non-words is used. As a manipulation, the word's individual component letters are mirrored either horizontally (ǝpɐuq - ABEND) or vertically (ɒdɘnb - ABEND) and an additional analysis is conducted to see whether mirror-priming effects are reduced or absent if a prime comprises reversible and/or confusable letters. Study 1 thus provides insights on whether the locus of the mirror-priming effect is lexical or pre-lexical by nature and whether implicit mirror-image reversals in reading also occur across the horizontal axis. Thus, study 1 will allow to refine theories on mirror-confusions in reading which make assumptions on whether confusions occur primarily across the letter's vertical mirror axis and on whether mirror-priming effects are lexical or pre-lexical by nature. Furthermore, results are important for current computational models of visual word recognition which do not consider that the confusability of letters is a parameter which affects visual word recognition.

1.5.2 Study 2

Study 2 taps into the early stages of lexical processing and addresses the question of *how* and implicitly *when* the perception of vertically and horizontally mirrored letters affects the reading process. In study 2, the question of *how* focuses on the mechanisms which underlie the reading of text with horizontally and vertically mirrored letters. We know from previous research that sentences with horizontally mirrored letters are read substantially slower than sentences with vertically mirrored letters (Kolers, 1968; Kowler & Anton, 1987) but it remains an open questions why this is the case. Experiments with individually presented words have shown that when letters within words are presented upside-down, this increases word length effects, indicating that readers process text more serially, in a letter-by-letter fashion, which is more attention demanding (Björnström et al., 2014; Navon, 1978). It remains unclear, however, whether word length effects are more pronounced when reading horizontally compared to vertically mirrored text. In study 2, the question of *how* is addressed by comparing word length effects during the reading of vertically and horizontally mirrored text compared to normal reading. Furthermore, the time-course of the mirror-interference effect remains largely unknown because previous eye-movement studies with mirrored text have not combined mirroring with a linguistic manipulation on the target word level (Chandra et al., 2020; Kowler & Anton, 1987). In study 2, the question of *when* mirror-interference effects occur is inferred by combining mirroring (as a visual manipulation) with a target-word frequency manipulation. For example, a word may be matched against items in the lexicon, by way of hypotheses or guesses, before individual letters have been identified. Such a result would provide an evidentiary basis for a cascaded processing architecture as suggested by Coltheart et al. (2001) and this would be reflected by interactive effects between mirroring and frequency on the word level. Alternatively, word recognition may happen only after individual letters of a word are identified. Such a result would provide an evidentiary basis for a strictly thresholded processing architecture as proposed by the E-Z reader model (Reichle et al., 2012) and this would be reflected by additive effects of mirroring and word frequency on the word level. Thus, by examining whether mirroring and word frequency produce additive or interactive effects on local eye-movement measures, study 2 sheds a light on the mechanisms through which text is recognized when being mirrored. Furthermore, the results of study 2 provide an evidentiary basis for models of eye-movements control which make predictions on either thresholded or cascaded processing during normal reading.

1.5.3 Study 3

Study 3 taps into later lexical processes and addresses the question of *if* and *how* the propensity of a word's letters to be mirror-confused affects the reading process in adults. As discussed above, masked mirror-priming studies with single mirror-letter manipulations have shown that adults selectivity suppress mirror-generalization for reversible letters (Soares et al., 2019; Perea et al., 2011) during the early stages of visual word recognition, leading to mirror-interference effects. This raises the question of whether such interference effects would also generalize to other letters which increase inter-letter-similarity when being mirrored and whether words which comprise many highly confusable letters (high confusability words) are recognized less efficiently than words which comprise mainly non-confusable letters (low confusability words). Previous research which has examined the impact of different mirror-transformations on reading processes has either examined how vertical and horizontal mirroring affects the recognition of a small subset of singly presented letters (Kolers & Perkins, 1969a, 1969b) or on how mirroring letters affects reading times of the entire sentence (Kolers, 1968; Chandra et al., 2020; Kowler & Anton, 1987). Importantly, those studies have not examined whether the variability in word reading times may be explained by a words average mirror-confusability. The reason for this is that answering this question would require a systematic quantification of the mirror-confusability of the entire Latin alphabet in order to manipulate the words' average mirror-confusability in a controlled experimental setting. One central aspect of study 3 is thus to develop and validate a metric which quantifies the mirror-confusability of each letter of the Latin alphabet when mirrored either vertically or horizontally. The metric provides a letter-based score which takes into account both the letter's recognition speed- and accuracy when being mirrored. Based on the score, a set of target words is categorized as either high- or low confusability words, depending on the average confusability score of the word's component letters. In a lexical decision task, response times and accuracy for high confusability words with vertically (e.g. ) and horizontally (e.g. ) mirrored letters is compared to low confusability words with vertically (e.g. ) and horizontally (e.g. ) mirrored letters. To see whether potential confusability effects generalize to a more ecologically valid reading task, the same words are embedded in mirrored carrier sentences which participants read while recording their eye-movements. Thus, study 3 examines the impact of mirror-confusability on word reading times and eye-movement behaviour in adults. Furthermore, it provides a novel metric which quantifies the mirror-confusability of the Latin alphabet by taking into account two variables that are associated with word recognition efficiency: Recognition speed and accuracy.

Together, the three studies enhance the limited literature on effects of mirroring on reading processes in adults by providing findings from experiments which tap into different stages of the word recognition process, including the earliest, pre-lexical processes. Furthermore, in this research project the concept of early, implicit, *horizontal* mirror-image confusions is included because previous mirror-priming studies have not examined horizontal mirror-priming effects. Moreover, the studies expand the methodological approaches taken in order to examine if and how general visual principles of mirror generalization interact with visual properties of a script such as the letter's sensitivity to mirror-reversals. In conjunction, the studies have the potential to yield valuable insights about if, how and when mirroring letters affects the reading process in adults.

Chapter 2

Priming Effects in Vertical and Horizontal Mirror-word Reading

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2.1 Abstract

We conducted two masked priming experiments to examine how the orthographic system processes mirrored letters. In both experiments, four different primes were used: an identity prime, an unrelated control prime, and two mirror-primes in which letters were either mirrored at their vertical or horizontal axis. Task was varied between experiments: In Experiment 1 we used a lexical decision task and in Experiment 2 we used a cross-case same-different match task. We expected to see priming effects in both mirror-conditions with stronger effects in the vertically than in the horizontally mirrored letters. In the lexical decision task, we observed priming effects only in the vertical, but not in the horizontal condition. In the same-different task, priming effects were present in both mirror-conditions and also for non-words. We discuss the implications of our findings for extant models of orthographic processing.

2.2 Introduction

The neuronal recycling hypothesis (Dehaene et al., 2005) postulates that the reading system makes use of the neural architecture of the visual system. This system has not evolved for reading, but is optimized to solve other visual tasks. A key feature of the visual system is that it exhibits *mirror-generalization* (Bornstein et al., 1978), that is, visual objects are typically not only recognized in their original form, but also when a corresponding mirror image is presented. Mirror-generalization allows for viewpoint invariant object-recognition and has been found in both humans (Standing et al., 1970) and non-human primates (Logothetis & Pauls, 1995). In reading and writing, by contrast, mirror-generalization can be dysfunctional, because a letter (e.g., "b") and its vertical ("d") or horizontal ("p") mirror image may represent a different and not the same letter. Mirror-generalization has thus to be unlearned or suppressed during reading acquisition (Dehaene et al., 2010; Perea et al., 2011; Duñabeitia et al., 2013). However, recent research has shown that normally presented and vertically mirrored text is processed similarly in the early, automatic stages of visual word recognition (Duñabeitia et al., 2011). But it is unclear whether this finding generalizes to horizontally mirrored text. To address this question, we conducted two masked priming experiments. In both experiments, targets were preceded by primes in which letters were either vertically or horizontally mirrored. In the first experiment, participants performed a lexical decision task and in the second experiment, they performed a cross-case same-different match task. We expected to see priming effects in both the vertical and the horizontal condition, with stronger priming effects for vertically mirrored letters. Furthermore, we assumed that mirror priming effects are pre-lexical and can be observed for both words and non-words.

For most non-artefacts (i.e., plants and animals, rocks and mountains, rivers and seas, the human body) the ability to distinguish an object from its vertical mirror-image is irrelevant because they are largely unaltered by left-right reflection (Corballis & Beale, 1976). It is, however, typically important for human-made objects (i.e., tools, symbols, and, in particular, letters). The ability to distinguish left from right is intimately related to the perception of symmetry which has been found to be anisotropic, favouring vertical over horizontal symmetry (Morin, 2018; Rossi-Arnaud et al., 2012; Corballis & Roldan, 1975; Julesz, 1971). Similarly, research on mirror-image discrimination in different species and humans has shown that the insensitivity to mirror-image reversals applies in particular to left-right (vertical) reversals (Corballis & Beale, 1976; Dehaene et al., 2005; Rollenhagen & Olson, 2000). In line with this hypothesis, adults have shown to reveal stronger difficulties in mirror-image discrimination tasks of left-right compared to up-down mirrored visual shapes (Gregory & McCloskey, 2010; Sekuler & Houlihan, 1968).

Corballis and Beale (1976) have argued that vertical mirror-generalization occurs because the structural formation of memory traces in the brain is symmetrized through interhemispheric mirror-image reversal. In other words, the brain per default encodes visual input together with its vertical mirror-image reversal in order to generalize from particular learned experiences to their mirror-images. According to the neuronal recycling hypothesis (Dehaene et al., 2005) cortical regions which were initially used for visual object recognition are recycled and re-used for the processing of written language. As a result, pre-literate children process words like other visual objects and, thus, letters and words are subjected to be mirror-reversed. Mirror-confusions in reading and writing have intrigued researchers since the beginning of the 20th century (Orton, 1925). Children who are not yet proficient readers (i.e., between the age of 5 and 10) tend to treat mirror images of letters and sometimes entire words (i.e. saw and wɒƨ) as equivalent.

Until present however, it is less clear whether automatic mirror processing still affects the early stages of the visual word recognition process in adults. Early orthographic processes can be examined using the masked priming paradigm (Forster & Davis, 1984). In masked priming, participants are presented very briefly (i.e. 50 ms) with a prime which is followed by a target-word. The prime is presented too briefly to be consciously perceived by the reader. To ensure that effects of the prime on target word recognition are based on orthographic rather than visual overlap, primes are presented in lower-case and targets in upper-case letters. Depending on the relationship between prime and target, priming effects can either be inhibitory or facilitatory. Identity priming (table-TABLE) usually produces strong facilitatory effects while unrelated control primes (house - TABLE) slow down target processing.

Several previous studies have used the masked priming paradigm to investigate processing of mirrored letters. For example, (Perea et al., 2011) used a masked priming lexical decision task to compare the recognition of target words which either comprised a reversible letter (e.g. i**d**ea - I**D**EA) or only non-reversible letters (e.g. a**r**ena - A**R**ENA). Primes were presented in three different conditions: Either the critical letter was presented normally (identity condition), vertically mirrored (mirror-condition) or it was replaced by an unrelated control letter (e.g. i**l**ea - IDEA) (control condition). Results show that primes which comprised a reversible letter that was mirrored slowed down target word processing more than primes which comprised an unrelated non-reversible letter. By contrast, primes which comprised a non-reversible mirrored letter did not slow down target word processing compared to the control condition, indicating that mirror-primes with reversible letters produce mirror-interference effects whereas mirror-primes with non-reversible letters do not. Perea and colleagues concluded that the suppression of mirror-generalization is applied selectively only to those letters that are reversible. Soares et al. (2019) replicated these effects in a (go/no-go) masked priming lexical decision task. In addition, they found that mirror-interference effects are mediated by the letter's left-right orientation (i.e. whether the letter faces to the right like *b* or to the left like *d*).

A second line of studies has used masked mirror priming in order to investigate potential facilitatory effects or mirroring for non-reversible letters. The underlying hypothesis is that mirrored letters also activate their mirror image because, as suggested by Corballis and Beale (1976), visual input is per default encoded together with its mirror-image reversal. As a consequence, processing of a (non-reversible) letter should be facilitated by a mirror prime compared to an unrelated control letter.

Using this logic, Duñabeitia et al. (2011) found facilitatory mirror priming effects using a masked priming go/no go semantic categorization task in which all internal letters of the prime were vertically mirrored while initial and final letters were presented in their normal position. Words comprised only non-reversible letters in order to avoid the aforedescribed mirror-interference effects. In the mirror-condition, internal letters were mirrored vertically, whereas in the control condition, the critical internal letters were replaced by other mirrored letters. Using event related potentials, Duñabeitia and colleagues could show that mirror-primes evoked early electrophysiological brain responses (N250 component) that were very similar to the effects evoked by identity primes, indicating that at an early stage of visual word recognition, vertical mirror-primes are processed like normally presented words. Duñabeitia and colleagues found similar results in a second experiment in which vertical mirror-primes consisted of an entirely mirrored word rather than a word with individually mirrored letters. However, they did not investigate letters which are horizontally mirrored.

Similarly, Winskel and Perea (2018) conducted two same-different masked priming experiments in which native English readers were presented with 4-letter word pairs. In their critical mirror-condition, the two internal letters (all non-reversible and non-symmetrical letters) were mirrored vertically whereas the initial and final letters were presented in their normal form. In the control condition, the two internal letters were replaced by two different letters which were also mirrored vertically. Winskel and Perea found facilitatory mirror priming effects which were, however, less pronounced than the identity prime effect. In a replication of this experiment with native readers of Thai (which is a writing system which does not comprise reversible letters) they found that mirror priming effects were even as strong as the identity prime effects. Again, the authors did only investigate the effects of vertical mirroring. In addition, they did not include non-words in their experiment.

Together, the above described studies show that vertical mirror-primes can affect visual word recognition and the observed effects can be inhibitory or facilitatory depending on whether the letter is reversible or non-reversible. There are two main questions which remain unresolved. First, we do not know whether the observed mirror priming effects generalize to primes with up-down (horizontally) mirrored letters. It is plausible to believe that horizontal mirroring would produce similar effects because there is a substantial body of evidence showing that horizontal mirror-image confusions are a common phenomenon in babies (Bornstein et al., 1978), 4 year old children (Huttenlocher, 1967), first grade children (Sekuler & Pierce, 1973), adults with a specific reading impairment (McCloskey & Rapp, 2000; McCloskey et al., 1995) and adults without a specific reading impairment (Gregory & McCloskey, 2010; Sekuler & Houlihan, 1968; Sekuler, & Pierce, 1973). The presence of a common perceptual difficulty in distinguishing both horizontal and vertical mirror-image reversals suggests that both types mirroring may be a residual aspect of mirror-generalization.

Second, it is not clear whether mirror priming effects only occur in words or also in non-words. Thus, we do not know whether mirror priming effects are generated during lexical or pre-lexical processing. The reason for this is that previous studies have used either a semantic categorization task or a same-different match task in which only words have been included. In addition, those studies that have used non-words in a lexical decision paradigm, used a go-no go task in which no responses for non-words are recorded. This is unfortunate because there are strong theoretical reasons to believe that mirror-priming effects should be located on the pre-lexical level. If mirror-generalization is not completely unlearned but rather selectively suppressed or inhibited for words and letters, then it is plausible to believe that at initial stages of processing, words are processed as other visual objects and therefore being subject to mirror-generalization (Duñabeitia et al., 2011; Poldrack et al., 1998). An early stage at which the perceptual system does not discriminate between letters in their normal orientation and mirrored letters would affect processes located within the interface between purely visual processing and pre-orthographic assembly of the letters and words (Duñabeitia et al., 2011).

In order to address these questions, we conducted two masked priming experiments using the same set of stimuli. In Experiment 1, participants performed a lexical decision task, while in Experiment 2 they performed a cross-case same-different match task. In each experiment, we included both horizontal (e.g.ǝpɐuq - ABEND) and vertical (e.g.ɐdǝnb - ABEND) mirror-primes which were entirely written in mirrored letters. We expected priming effects for both types of mirroring, but also that vertical mirror-primes might be stronger. This prediction is in line with Corballis and Beale (1976), Dehaene et al. (2005) and Rollenhagen and Olson (2000), who suggest that the perceptual system is particularly biased towards vertical mirror-generalization.

Our predictions on the cognitive locus of mirror priming effects are less clear. If mirror priming effects are lexical, we would expect to see priming effects only for words, but not non-words (i.e. because non-words are not represented in the mental lexicon). If, by contrast, mirror priming effects are pre-lexical, they should be observable for both words and non-words.

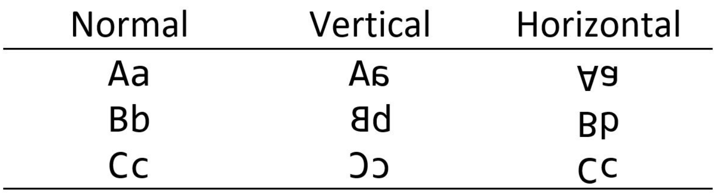
Our study differs from previous experiments by the fact that not only single, individual letters in the prime have been mirrored, but all letters at the same time. Because target words included both reversible (*b*, *d*, etc.) and non-reversible letters (*r*, *k*, etc.), we checked in an additional analysis whether mirror priming effects were moderated by the confusability of a word.

2.3 Experiment 1

2.3.1 Method

Participants We recruited adult participants via the online system of the University of Göttingen for an online-experiment in which 30 adults (age:M = 24.5, SE = 5.6, years; 25 female) participated for course credit. All participants were German native speakers, and had normal or corrected to normal vision. The study was approved by the ethics committee of the University of Göttingen. At the beginning of the study, participants provided informed consent electronically.

FIGURE 2.1: Example letters in each of the customized mirror-fonts.



Materials We selected 192 nouns from the Digital Dictionary of the German language (DWDS) (Geyken, 2007) that served as target words in the lexical decision task. All words had a normalized lemma frequency > 35. In addition, we created 192 non-words by substituting one or two letters of a different set of existing words. Nouns comprised only stems and were between 4 and 7 letters long. Words had a bigram frequency of *M* = 28.17, *SD* = 4.81 (range: 14.60 - 38.86) and non-words had a bigram frequency of *M* = 28.84, *SD* = 4.85, (range: 17.17-41.88).

Each word and non-word target was preceded by four different primes. Targets were always presented in upper-case, while primes were always presented in lower-case letters. In the identity condition, the prime was the target word itself (vater - VATER). In the vertical mirror-condition, letters were mirrored around their vertical mirror-axis whereas in the horizontal mirror-condition letters were mirrored around their horizontal mirror-axis. For the two mirror-prime-conditions, we used the open source software Font Forge to create new customized vertical and horizontal mirror-fonts. An example of the font used in the Normal, Vertical and Horizontal condition is shown in Figure 2.1. In the control condition, the prime was an unrelated word (halle - LICHT) or non-word (stend - PFURD). Control words were the same words as in the identity condition but they were assigned to a different target.

To avoid repetition of the targets within the experiment, we used a Latin square design with four lists, such that each participant saw each target once in one of the four prime-conditions. However, across participants, each target was presented in combination with all four primes. Each participant saw 192 words and 192 non-words with 48 words and 48 non-words in each of the four prime-conditions.

As a consequence, the present experiments are reasonably well-powered and the number of overall observations in each cell ($30 \times 48 = 1440$) is close to the number of data points recommended by Brysbaert and Stevens (2018) in order to observe a 16 ms orthographic priming effect with an power of $1 - \beta = .8$ at $\alpha = .05$.

Confusability score As elaborated above, all letters in a word were mirrored in our study, irrespective of whether they were reversible or not. In order to investigate whether priming effects were moderated by the number of reversible and non-reversible letters in a word, we computed an overall *confusability* score which summarizes how many letters in a word are reversible, non-reversible, or symmetrical, which indicates how easy a letter can be confused with another letter. Based on the score, targets were then categorized as high or low confusability targets. Values were computed for each target and each mirror-condition separately in the following way.

In a first step, each letter was coded using a (-1, 0, 1) coding scheme according to its mirror-confusability. The code 1 was assigned to reversible letters (e.g., *b, d, p, q*) while the code 0 was given to non-reversible letters (e.g., *r, c, g, k*). In addition, the code -1 was used for symmetrical letters (e.g., *x, o, l*), which stay invariant during mirroring. As some letters are confusable with other letters when mirrored horizontally, but not vertically (e.g., *f/t*), the coding was done independently for the vertical and the horizontal condition.

In a next step, the mean confusability of a word was computed separately for the vertical and the horizontal condition by averaging the codes of words' component letters. Higher confusability scores thus indicate a higher proportion of reversible letters and lower proportion of symmetrical letters within a word. For example, the word "abend" would be coded as (0, 1, 0, 0, 1) in the vertical condition and with (0, 1, 0, 1, 1) in the horizontal condition, leading to a confusability score of 0.4. in the vertical and of 0.6 in the horizontal condition. Average confusability is typically higher in the horizontal than in the vertical condition because more letters are reversible when mirrored horizontally than vertically.

In a last step, targets in the vertical and horizontal condition were categorized as high- or low-confusable words based on median split of each scores (using a cut-off of 0 in the vertical, and of 0.25 in the horizontal condition).

Procedure Due to the ongoing Covid-19 pandemic, the experiment was conducted in as an online study. Participants performed a lexical-decision task in which they were instructed to decide as fast and accurately as possible whether the items presented on the screen were words or non-words. There were four blocks which were separated by short pauses. In each block, participants responded to 48 words and 48 non-words. In order to respond, a key press of the letter K for words and the letter D for non-words was required. Response latencies and answers were recorded. All stimuli were presented in white, in the customized mirror-font with the font height set to 3.89% of the screen height. The background was black. Forward masks were created using hashes, and their length was identical to the length of the targets. Forward mask were presented for 500 ms. Immediately after this, the prime was

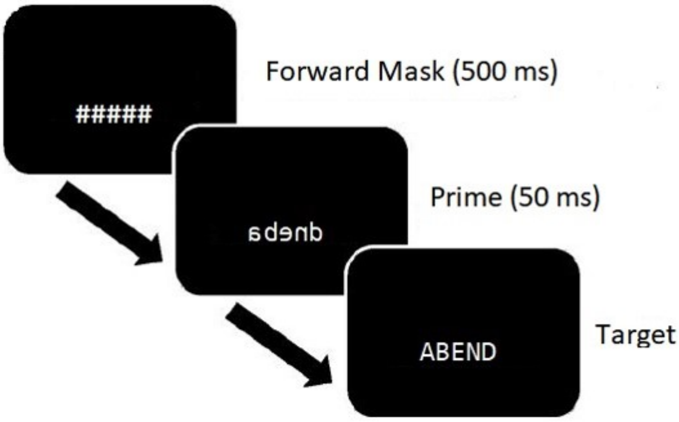


FIGURE 2.2: Schematic representation of a trial in the masked priming lexical decision task.

presented for 50 ms. After that, the 50 ms target was then presented until a response was given (see Figure 2.2 for a schematic representation of a trial). Participants were not informed about the presence of the masked prime. In a survey that followed the experiment, none of the participants reported awareness of the masked primes. A different random order for the items was generated for each participant. Each participant received 8 practice trials prior to the 384 experimental trials. The study was approved by the Ethics Committee of the University of Göttingen.

2.3.2 Results

Results were analysed using (generalized) linear mixed effects models using the lme4 package (Bates et al., 2015) for R (R Core Team, 2013). For response accuracy, a generalized linear mixed effects Model with a binomial link function was used. Correct log-transformed response times were analysed using a linear mixed effects model. The data were cleaned in two stages. First, outliers were discarded by excluding all trials that were extremely fast (<=300ms) or slow (>=3000ms), which excluded 0.2% of all trials. In the second step, model criticism based on a simple model including only random intercepts for participants and items was used, excluding all data points exceeding 2.5 standard deviations. In this step, 2% of the trials were excluded.

In the final models we entered prime-condition (4: identity vs. vertical vs. horizontal vs. control) and word-type (2: word vs. non-word) as effect-coded fixed effects. Random effects comprised random intercept slopes for prime-condition for both participants and items. The significance of the effects was evaluated using Wald tests and the Anova function of the car package using type III model comparisons. Post hoc comparisons were conducted using the glht function in the multcomp package (Hothorn et al., 2008). The model mean RTs and accuracies are shown in Figure 2.3 and in Table 2.1, while the results from the linear mixed effect models are shown in Table 2.2.

In an additional analyses, we divided the responses in the vertical and horizontal condition into high- and low-confusability words in order to investigate whether priming effects were moderated by confusability. The corresponding models included the extended prime-condition (6: identity vs. vertical high-confusability vs. vertical low-confusability vs. horizontal high-confusability vs. horizontal low-confusability) and word-type (2: word vs. non-word) as effect-coded fixed effects. The model mean RTs and accuracies are shown in Figure 2.3 and in Table 2.3, while the results from the linear mixed effect models are shown in Table 2.4.

Reaction times Results showed a main effect of word-type.

Words, M = 570 ms, SE = 18 ms, were recognized Δ = 82 ms faster, than non-words, M = 652 ms, SE = 7 ms.

In addition, the main effect of prime condition as well as the interaction between prime condition and word type was significant.

For words, planned post-hoc contrasts revealed an identity priming effect of Δ = 39 ms, z = 9.264, $p < .001$ and a vertical mirror priming effect of Δ = 13 ms, z = 3.025, p = .002. The vertical mirror priming effect was smaller than the identity priming effect, z = 6.576, $p <$ .001. The horizontal mirror priming effect was not significant, z = 0.137, p = .891.

For non-words, planned post-hoc contrasts revealed a significant identity priming effect of Δ = 17 ms, z = 3.511, $p < .001$, while the vertical mirror priming effect was not significant, Δ = 8 ms, z = 1.508, p = .132. The horizontal mirror priming effect of Δ = 11 ms, z = 2.123, p = .033 just reached significance, but was rather small.

In an additional analysis we investigated whether mirror priming effects differed between high- and low confusability targets. This was not the case for both vertical and horizontal priming effects in words and non-words (see Table 2.3).

Accuracy Results showed a significant main effect of word-type.

Recognition accuracy for words M = 97.98%, SE = 0.50%, was Δ = 0.96% higher than for non-words, M = 97.02 %, SE = 0.67%.

In addition, the main effect of prime condition as well as the interaction between prime condition and word type was significant.

TABLE 2.1: Experiment 1: Mean Model Reaction Times (Milliseconds), Accuracy (%) and Priming Effects to Word and Non-word Targets (SEs in Parentheses)

	Words				Non − Words			
prime-condition	*Acc*	Δ	*RTs*	Δ	*Acc*	Δ	*RTs*	Δ
Identity	99.03^{a} (0.2)	1.61***	544^{a} (14)	39***	97.45^{a} (0.5)	0.04	641^{a} (16)	18***
Vertical	98.12^{b} (0.4)	0.7	569^{b} (14)	13**	97.05^{a} (0.7)	0.44	651^{b} (16)	8
Horizontal	97.25^{b} (0.6)	0.17	582^{c} (14)	1	96.59^{a} (0.7)	0.9	647^{b} (16)	12*
Control	97.42 (0.6)		582 (15)		97.49 (0.6)		659 (17)	

Note. Δ = Size of Priming Effect. Different letters indicates significant contrast.

TABLE 2.2: Experiment 1: Results from Linear Mixed-Effects Models (χ^2 Wald tests) for Word Accuracy and RTs in Experiment 1

	Accuracy		*RTs*	
Effect (df)	χ^2	p	χ^2	p
Prime-condition (3)	12.22	$< .01$**	89.22	$< .001$***
Word-type (1)	6.53	0.01*	424.98	$< .001$***
Prime-condition x Word-type (3)	10.94	0.012*	34.05	$< .001$***

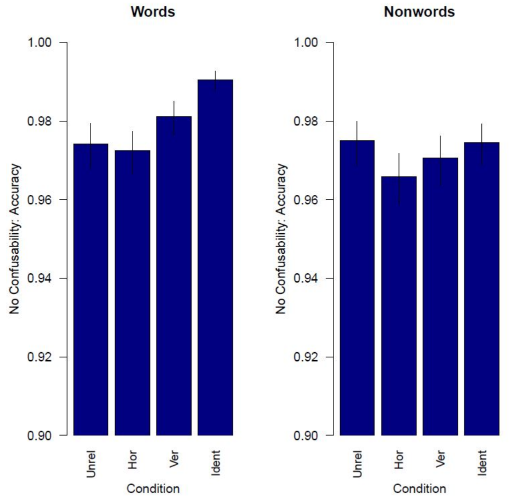
TABLE 2.3: Confusability Analysis Experiment 1: Mean Model Reaction Times (Milliseconds), Accuracy (%) and Priming Effects to Word and Non-word Targets (SEs in Parentheses)

	Words				Non − Words			
Prime-condition	*Acc*	Δ	*RTs*	Δ	*Acc*	Δ	*RTs*	Δ
Identity	98.93 (0.4)	1.65	544 (14)	39***	97.09 (0.9)	97.09	644 (16)	17***
Vertical								
High Confusability	97.37^{a} (1.1)	0.09	573^{a} (15)	10	97.24^{a} (1.3)	0.03	656^{a} (17)	5
Low Confusability	98.73^{a} (0.5)	1.45	568^{a} (14)	15**	97.76^{a} (0.9)	0.55	651^{a} (15)	8
Horizontal								
High Confusability	98.20^{a} (1.1)	0.92	583^{a} (16)	0	97.22^{a} (1.0)	0.01	647^{a} (17)	14*
Low Confusability	96.88^{a} (0.9)	0.4	582^{a} (14)	1	96.47^{a} (0.1)	0.74	651^{a} (15)	10
Control	97.28 (0.8)		583 (15)		97.21 (0.8)		661 (17)	

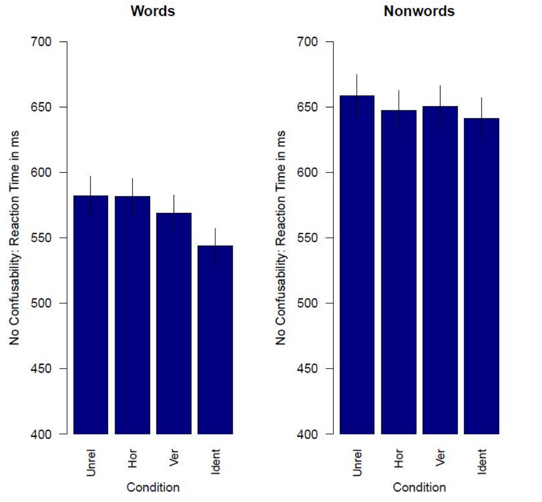
Note. Δ = Size of Priming Effect. Different letters indicates significant contrast.

For words, planned post-hoc contrasts revealed an identity priming effect of Δ = 1.5%, z = -3.556, $p < .001$ while neither the vertical mirror priming effect, Δ = 0.45%, z = -0.961, p = 0.337, nor the horizontal mirror priming effect, Δ = 0.29%, z = 0.577, p = 0.564, was significant. For non-words the identity priming effect was not significant, z = 0.447, p = .655.

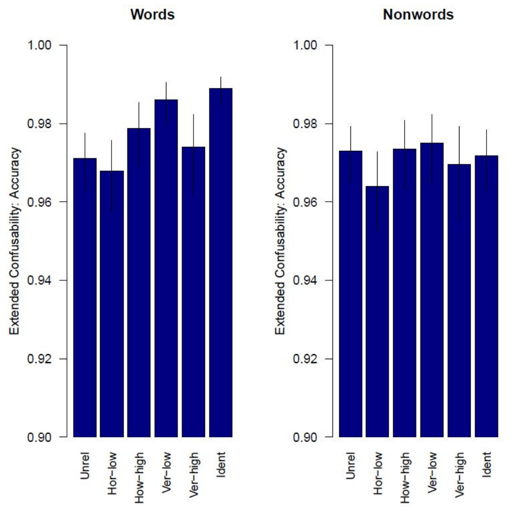
An additional analysis differentiating between high- and low-confusability targets showed that neither the vertical nor the horizontal priming effect was moderated by confusability.



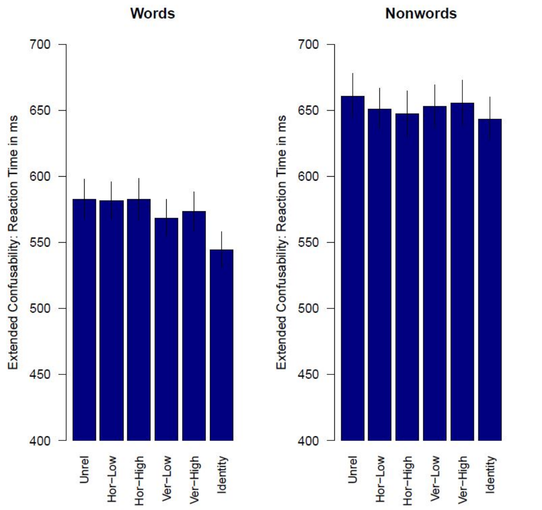
(a) Without Confusability: Accuracy



(b) Without Confusability: Reaction Time



(c) Confusability Analysis: Accuracy



(d) Confusability Analysis: Reaction Time

FIGURE 2.3: Plots a-d:Experiment 1 Mean Model Accuracy and Reaction Times (Milliseconds) for non-words and words in the lexical decision task.

TABLE 2.4: Confusability Analysis Experiment 1: Results from Linear Mixed-Effects Models (χ^2 Wald tests) for Word Accuracy and RTs in Experiment 1

	Accuracy		*RTs*	
Effect (df)	χ^2	p	χ^2	p
Extended Prime-condition (5)	15.58	$< .01$**	86.66	$< .001$***
Word-type (1)	4.40	$< .05$*	382.07	$< .001$***
Extended Prime-condition x Word-type (5)	10.55	.061	33.70	$< .001$***

2.3.3 Discussion

The results from Experiment 1 are rather clear-cut. First, for words we found vertical, but not horizontal mirror priming effects in both response time and accuracy. Vertical priming effects were, however, not as pronounced as the identity priming effects. For non-words, by contrast, mirror priming effects were rather weak and inconsistent. Finally, both vertical and horizontal priming effects were not affected by words' average confusability.

By and large, this pattern replicates important results from previous studies which found facilitatory priming effects for primes with vertically mirrored letters (Duñabeitia et al., 2011; Winskel & Perea, 2018). However, our study shows that mirror priming effects can also be found when all, but not only single letters are mirrored. By contrast, horizontal mirror priming effects are rather weak or non-existent.

This is the first masked priming study that has investigated mirror priming effects for non-words. These were generally absent which seems to indicate that mirror priming effects are confined to words and are lexical by nature (Perea et al., 2011).

Finally, our results show that average word confusability did not moderate mirror priming effects which were facilitatory and equally strong for high- and low-confusable words. This finding does not contradict studies which found inhibitory priming effects for individual reversible letters (Perea et al., 2011; Soares et al., 2019). It shows, however, that these effects might be too subtle in order to be detected on the word-level.

2.4 Experiment 2

Overall, findings from Experiment 1 indicate that mirror priming effects might be lexical and confined to vertical mirroring. However, we also found clear identity priming effects and weak, but significant horizontal mirror priming effects for non-words which may be taken as an indicator that mirror priming effects also operate on the pre-lexical processing stage. In order to address this issue, we conducted a second experiment with the same set of items as in Experiment 1 but using the same-different match task instead of lexical decision. As argued by Kinoshita and Norris (2012), the same-different task is particularly suited for studying early, pre-lexical processing stages. In contrast to the lexical decision task, participants do not have to decide whether the target is a word or a non-word, but whether it matches a previously displayed reference stimulus. This difference has a huge impact on the procedural level. In order to decide whether the target is a word or not, the reader does not have to identify *which* word the input is. Thus, the identification of a word's individual component letters is not necessarily required by the lexical decision task. By contrast, the same-different match task requires the observer to recognize each individual letter, because differences between the reference and the target stimulus can occur everywhere in the target. Visual, pre-lexical effects are thus generally boosted and priming effects are typically observed for both words and non-words (Kinoshita & Norris, 2012). We thus expected that mirror priming effects would be generally larger and be observed for both words and non-words.

2.4.1 Methods

Participants We recruited a new sample of 42 adult participants via the online recruiting system of the University of Göttingen for an online-experiment. Participants had a mean age of M = 21.17 years (SD = 2.74; 33 female), were German native speakers, and had normal or corrected to normal vision.

Materials The same materials as for Experiment 1 were used in Experiment 2. In order to create *different* trials in the same-different task, we added 192 reference words which were nouns from the Digital Dictionary of the German language (DWDS) (Geyken, 2007). All reference words had a normalized lemma frequency > 20 and had similar lemma frequencies as the target words, t = 1.01, df = 322.57, p = .31. Each reference-target word pair had the same length and did not comprise identical letters in the same position (i.e. armee-staat). Non-word references were created by substituting each vowel with a different vowel and each consonant with different consonant. Thus, as for words, reference and target non-words had the same length and did not comprise identical letters in the same position (i.e., arage-unoki).

To avoid repeating targets within the experiment, we used a Latin square design with eight item lists, such that each participant saw each target once in one of the four prime-conditions and in either the same or the different condition. However, across participants, each target was presented in combination of all conditions. Overall, each participant saw 192 words and 192 non-words with 24 words and 24 non-words in each of the four prime-conditions in the same and different condition respectively.

Procedure Again, the experiment was conducted in an online study. Participants performed a cross-case same-different match task in which they were presented with a pair of letter strings, one after another. Participants were instructed to decide as fast and accurately as possible whether the two letter strings were identical or different. In each block, participants responded to 48 words and 48 non-words. In order to respond, a key press of the letter K for words and the letter D for non-words was required. Response latencies and answers were recorded. Primes and references were always presented in lowercase whereas targets were presented in uppercase. All stimuli were presented in white, in the customized

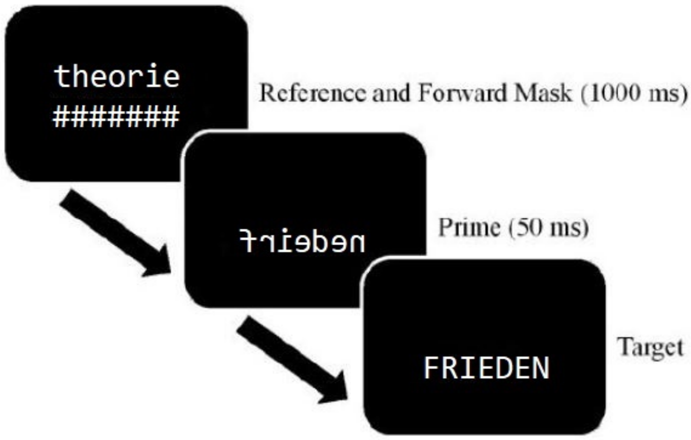


FIGURE 2.4: Schematic representation of a trial in the masked priming cross-case same different match task.

mirror-font with the font height set to 3.89% of the screen height. The background was kept black. The reference was presented for 1000 ms, together with the forward mask that was presented for the same time in the line below the reference. After the 1000 ms, the reference and the mask vanished and the prime appeared at the location of the forward mask, which was presented for 50 ms. The target was then presented in this same location until a response was given (see Figure 2.4 for a schematic representation of a trial). Participants were not informed of the presence of the masked prime. In a survey that followed the experiment, none of the participants reported awareness of the masked primes. A different random order of items was generated for each participant. Each participant received 8 practice trials prior to the 384 experimental trials. The study was approved by the Ethics Committee of the University of Göttingen.

Analyses As effects are usually only observed in the same condition in the same-different task, only data from trials in the same condition were analysed. Responses were analysed using (generalized) linear mixed effects models. The cleaning procedure for correct response times was identical to Experiment 1, leading to an exclusion of 3.1% of responses overall. The models for the analyses were specified in the same way as in Experiment 1, with prime-condition and word-type as effect-coded fixed effects and random intercepts and slopes for participants and items. Model mean RTs and accuracy are shown in Table 2.5 and Figure 2.5, results from linear mixed-effects model are provided in in Table 2.6.

Again, in an additional analysis we investigated whether priming effects were moderated by average letter confusability. The model mean RTs and accuracies are shown in Table 2.7, while the results from the linear mixed effect models are shown in Table 2.8.

TABLE 2.5: Experiment 2: Mean Model Reaction Times (Milliseconds), Accuracy (%) and Priming Effects to Word and Non-word Targets in Same-responses (SEs in Parentheses)

	Words				*Non − Words*			
prime-condition	*Acc*	Δ	*RTs*	Δ	*Acc*	Δ	*RTs*	Δ
Identity	97.29[a] (0.6)	4.58***	437[a] (11)	65***	96.80[a] (0.7)	6.30***	484[a] (13)	60***
Vertical	97.79[a] (0.6)	5.08***	463[b] (12)	39***	95.99[a] (0.9)	5.49***	501[b] (13)	43***
Horizontal	97.22[a] (0.6)	4.51***	467[b] (12)	35***	93.93[b] (1.1)	3.43**	507[b] (13)	37***
Control	92.71 (1.2)		502 (11)		90.50 (1.4)		544 (12)	

Note. Δ = Size of Priming Effect. Different letters indicates significant contrast.

TABLE 2.6: Experiment 2: Results from Linear Mixed-Effects Models (χ^2 Wald tests) for Word RTs and Accuracy for Same-responses in Experiment 2

	Accuracy		*RTs*	
Effect (df)	χ^2	p	χ^2	p
Prime-Condition (3)	55.21	$< .001$***	185.63	$< .001$***
Word-Type (1)	19.01	$< .001$***	238.62	$< .001$***
Prime-Condition x Word-Type (3)	4.73	.192	3.55	.314

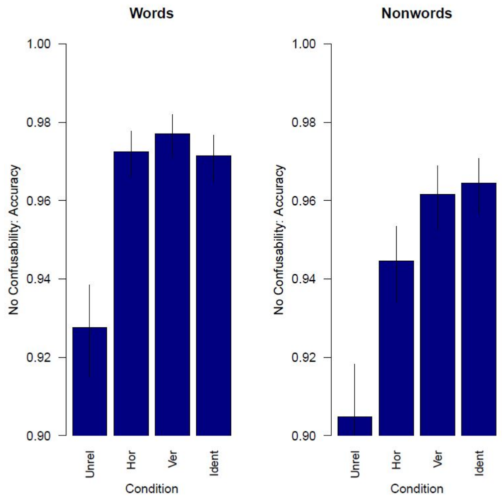
TABLE 2.7: Confusability Analysis Experiment 2: Mean Model Accuracy (%), Reaction Times (Milliseconds) and Priming Effects for Word and Non-Word Targets (SEs in Parentheses)

	Words				*Non − Words*			
Prime-condition	*Acc*	Δ	*RTs*	Δ	*Acc*	Δ	*RTs*	Δ
Identity	97.34 (0.8)	4.3***	437 (11)	64***	96.74 (0.9)	5.98***	484 (13)	60***
Vertical								
High Confusability	98.56[a] (0.9)	5.56***	462[a] (12)	40***	95.50[a] (1.9)	4.74	514[a] (14)	30***
Low Confusability	97.74[a] (0.9)	4.78***	463[a] (12)	40***	97.05[a] (1.0)	6.29***	496[b] (13)	48***
Horizontal								
High Confusability	97.50[a] (1.0)	4.54**	469[a] (12)	31***	94.00[a] (1.7)	3.24	524[a] (14)	20**
Low Confusability	97.20[a] (1.0)	4.24***	465[a] (12)	36***	94.64[a] (1.4)	3.88*	495[b] (13)	49***
Control	92.96 (1.7)		502 (11)		90.76 (2.1)		544 (12)	

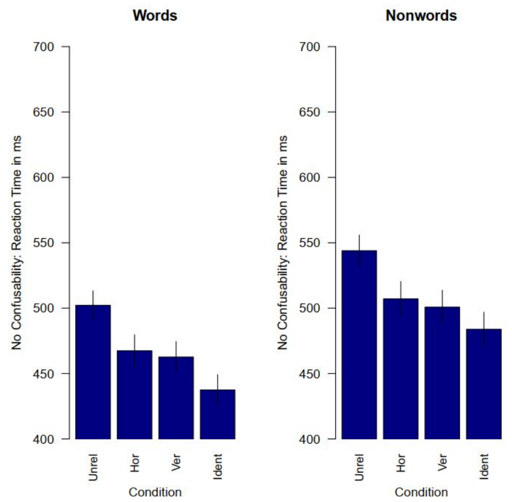
Note. Δ = Size of Priming Effect. Different letters indicates significant contrast.

TABLE 2.8: Confusability Analysis Experiment 2: Results from Linear Mixed-Effects Models (χ^2 Wald tests) for Word RTs and Accuracy for Same-responses in Experiment 2

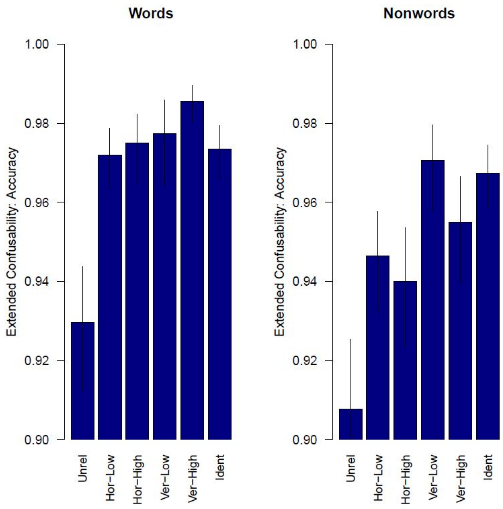
	Accuracy		*RTs*	
Effect (df)	χ^2	p	χ^2	p
Extended Prime-Condition (5)	31.03	$< .001$***	177.25	$< .001$***
Word-Type (1)	19.80	$< .001$***	224.48	$< .001$***
Extended Prime-Condition x Word-Type (5)	6.23	.285	10.92	.05



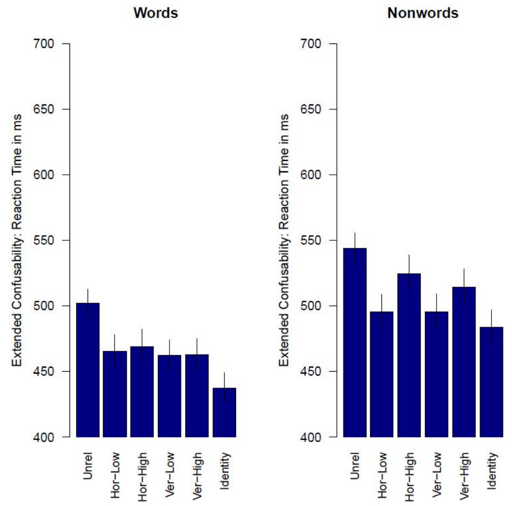
(a) Without Confusability: Accuracy



(b) Without Confusability: Reaction Time



(c) Confusability Analysis: Accuracy



(d) Confusability Analysis: Reaction Time

FIGURE 2.5: Plots a-d:Experiment 2 Mean Model Accuracy and Reaction Times (Milliseconds) for non-words and words in the same different match task.

2.4.2 Results

Reaction times Results showed a main effect of word-type. RTs for words, M = 467 ms, SE = 11 ms, were Δ = 41 ms faster than for non-words, M = 508 ms, SE = 12 ms. In addition, the main effect of prime-condition was significant, while the interaction between word-type and prime-condition was not. Thus, in contrast to Experiment 1, priming effects for words and non-words did not differ from each other. However, in order to ease the comparability between experiments, we also analysed priming effects for words and non-words separately.

For words, planned post-hoc contrasts revealed an identity priming effect of Δ = 65 ms, z = -11.6, $p < .001$ as well as a vertical mirror priming effect of Δ = 39 ms, z = 7.684, $p < .001$ and a horizontal mirror priming effect of Δ = 35 ms, z = -6.157, $p < .001$. The vertical and the horizontal mirror priming effect did not differ from each other, z = 1.06, p = .289, and were both smaller than the identity priming effect, all z = -6.807, $p < .001$.

For non-words, post-comparisons revealed a substantial identity priming effect of Δ = 60 ms, z = -9.737, $p < .001$, as well as a vertical mirror priming effect of Δ = 43 ms, z = 7.643, $p < .001$, and a horizontal mirror priming effect of Δ = 37 ms, z = -5.984, $p < .001$. The vertical and the horizontal mirror priming effect did not differ from each other, z = 1.275, p = .202, but both were smaller than the identity priming effect, all z = -3.448, $p < .001$.

An additional analysis differentiating between high- and low-confusability targets in the vertical and horizontal condition showed that both vertical and horizontal priming effects were generally larger for low- than for high-confusable targets (see Table 2.7). This difference was significant in non-words (horizontal mirror priming, z = -3.866, $p < .001$, vertical mirror priming, z = 2.238, p = 0.025) while in words, priming effects did not differ between high- and low-confusable targets (horizontal mirror priming, z = -0.547, p = .584, vertical mirror priming, z = 0.079, p = .937).

Accuracy Results showed a main effect of word-type. Words, M = 72.43%, SE = 11.90 %, were recognized Δ = 0.36% more accurately than non-words, M = 72.07%, SE = 11.92 %. In addition, the main effect of prime-condition was significant, while the interaction between prime-condition and word-type was not. However, for the sake of consistency, we report priming effects separately for words and non-words.

For words, we found an identity priming effect of Δ = 4.58%, z = 4.202, $p < .001$, as well as a vertical mirror priming effect of Δ = 5.08%, z = -4.911, p = .001, and a horizontal mirror priming effect of Δ = 4.51%, z = 4.581, $p < .001$. Vertical and horizontal mirror priming effects did not differ from each other, z = -0.903, p = .366, and were similarly strong as the identity priming effect, both z = -0.775, p = .438.

For non-words, we found an identity priming effect of Δ = 6.30%, z = 4.895, $p < .001$, a vertical mirror priming effect of Δ = 5.49%, z = -4.144, $p < .001$, and a horizontal mirror priming effect of Δ = 3.43%, z = 2.692, p = .007. The identity and the vertical mirror priming effect did not differ significantly from each other, p = .722, while the horizontal mirror priming effect was slightly smaller, z = 3.192, p = .001.

In an additional analysis we investigated whether mirror priming effects differed between high- and low confusability targets. This was not the case for both vertical and horizontal priming effects in words and non-words (see Table 2.7).

2.4.3 Discussion

Again, the effects reported in Experiment 2 are rather straightforward, but rather different from the effects found in Experiment 1. First, we found substantial and equally pronounced mirror priming effects in the vertical and the horizontal priming condition which, however, were not as pronounced as the identity priming effects. Second, we observed similar priming effects for words and non-words. Indeed, priming effects for words and non-words were nearly identical, differing only by a few milliseconds (see Table 2.5). Finally, we saw that mirror priming effects were moderated by letter confusability. Generally, priming effects were smaller for high- than for low-confusability non-words.

Overall, the results of Experiment 2 indicate that mirror priming effects are pre-lexical and occur for both vertically and horizontally mirrored letters. This finding directly extends the findings reported by Duñabeitia et al. (2011) and Winskel and Perea (2018) who, however, only investigated vertical mirror priming. We also found that mirror priming effects were stronger for low- compared to high-confusability non-words. This is in line with the findings of Perea et al. (2011) and Soares et al. (2019), who showed that mirroring of reversible letters produces interference effects which might lead to decreased mirror priming effects in the high-confusable condition.

2.5 General Discussion

In the present study, we conducted two experiments in order to examine how letter mirroring impacts visual word recognition and, in particular, the early stages of orthographic processing. We used a masked priming paradigm using primes with vertically and horizontally mirrored letters. The task was varied between experiments: In Experiment 1 we used a lexical decision task whereas in Experiment 2 we used a cross-case same-different match task. In the lexical decision task, we found vertical, but not horizontal mirror priming effects for words. In the same-different task, by contrast, we found both vertical and horizontal mirror priming effects for both words and non-words. In addition, mirror priming effects were moderated by confusability in non-words, with weaker effects for words comprising more reversible letters.

Thus, a first general conclusion from our study is that mirror priming effects vary with task. As pointed out by Kinoshita and Norris (2012), different tasks tap into different processes of the word recognition process. The same-different match task requires the observer to recognize each individual letter with a high degree of certainty and this makes the task particularly suitable for examining the early, pre-lexical processes of word recognition. The fact that mirror priming effects are stronger here indicates that the locus of the mirror priming effects is pre-lexical and that the lexical decision task is not sensitive enough to capture the entire spectrum of the mirror priming effect.

Secondly, and in line with this, we found that mirror priming effects occur for both words and non-words. This indicates that mirror priming effects are generated at the feature- or letter-level of processing and are independent of top-down-activation from the orthographic lexicon. Apparently, mirror-generalizations cannot be entirely suppressed at the early, pre-lexical stage of orthographic processing. As a consequence, mirrored letters are processed as simple allographs by the letter detectors (Duñabeitia et al., 2011).

Thirdly, we extend previous research by showing that vertically (left-right) and horizontally (up-down) mirrored letters evoke equally strong priming effects, indicating that during early feature- and letter processing, general visual principles of mirror-generalization (Dehaene et al., 2005) operate both vertically and horizontally. This suggests that at the initial stages of processing, letter-features are activated irrespective of their left-right or up-down orientation, following general visual principles of mirror-generalization (Duñabeitia et al., 2011; Poldrack et al., 1998).

And finally, we found stronger mirror priming effects for low- than for high-confusable non-words. This shows that priming effects are reduced when targets comprise reversible letters. This reduction is presumably driven by interference effects at the letter-level caused by the simultaneous activation of competing letter representations (Perea et al., 2011; Soares et al., 2019). This finding also shows that mirror-generalization is not selectively suppressed for reversible letters and that the same general principles of the visual processing apply to all letters (Duñabeitia et al., 2011; Poldrack et al., 1998).

Overall, the pattern of findings is consistent with the assumptions of the Interactive Activation Model (IAM) (McClelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). The IAM assumes that a letter node is activated in response to the perception of features which match those of a letter's abstract representation. Given the tendency of the visual system to mirror-generalize visual input, non-reversible letters (e.g. a, s, c) immediately activate the corresponding abstract letter representation, because there is no inhibitory link between a non-reversible letter and its mirror-image counterpart. Reversible letters (b, d, p, q, n, u), by contrast, activate a competing letter representation which produces inhibitory effects at the letter level.

Similarly, the Bayesian Reader Model (Norris, 2006; Norris & Kinoshita, 2008, 2012) assumes that readers integrate information through the computation of conditional probabilities based on Bayes theorem, and the output of this computation is the likelihood of a specific hypothesis given the evidence. The evidence corresponds to the visual input which the reader perceives. In contrast to the IAM, the Bayesian Reader assumes that both the prime and the target are processed as a single object. Thus, both the upper case letter in the target and the lower case letter in the prime provide evidence towards the hypothesis that the target contains a particular abstract letter representation in a specific location. Mirror-primes introduce less uncertainty to recognition than control primes because mirror-reversals of letters comprise the same features and have the same overall visual shape as letters in their normal position. However, the presence of reversible letters within the prime increases the likelihood that a different letter is present in a specific location within target. This leads to an increased level of noise for reversible compared to non-reversible letters which in turn decreases mirror priming effects in high-confusability words.

So, how are mirror priming effects generated in such models? First, results indicate that at the level of features, the coding scheme is highly flexible because it seems to activate individual features regardless of the reader's viewpoint (Perea et al., 2011). For the Latin alphabet, a set of distinctive features has been identified. These features include terminations, straight lines, curved lines, and oblique lines, as well as intersections (Fiset et al., 2008; Gibson, 1969; Briggs & Hocevar, 1975). For the distinction of oblique lines, the direction of mirroring is irrelevant because / equals \ irrespective of the direction of mirroring. By contrast, curved lines have, despite their shape, another additional relevant characteristic which is the opening direction (either up-down or left-right) of their arc. If letter features are activated regardless of one's viewpoint, then the feature  would partially activate , , and , whereas straight vertical and horizontal lines do not change their orientation when mirrored either way. In this example, the horizontal mirror prime of the letter $< f >$ (e.g. ) likely activates the two competing abstract letter representations f/F and t/T whereas the vertical mirror prime (e.g. ) activates only the abstract letter representation f/F. It has to be noted, though, that the current implementation of the IAM only includes upper-case letters and thus, a set of lower case would need to be added (Perea et al., 2011).

In conclusion, we extended previous masked priming research (Soares et al., 2021, 2019; Perea et al., 2011; Duñabeitia et al., 2011) by investigating the effects of both vertical and horizontal mirror primes and in both words and non-words in a lexical decision and a same-different match task. We found vertical and horizontal mirror priming effects for both words and non-words in the same-different task. This indicates that mirror priming effects are pre-lexical by nature and result from applying general principles of visual processing at the feature- and the letter-level.

Chapter 3

Reading vertically and horizontally mirrored text: An eye movement investigation

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3.1 Abstract

This study examined the cognitive processes involved in reading vertically and horizontally mirrored text. We tracked participants' eye movements while they were reading the Potsdam Sentence Corpus which consists of 144 sentences with target words that are manipulated for length and frequency. Sentences were presented in three different conditions: In the normal condition, text was presented with upright letters, in the vertical condition, each letter was flipped around its vertical (left-right) axis while in the horizontal condition, letters were flipped around their horizontal (up-down) axis. Results show that reading was slowed down in both mirror conditions and that horizontal mirroring was particularly disruptive. In both conditions, we found larger effects of word length than in the normal condition indicating that participants read the sentences more serially and effortfully. Similarly, frequency effects were larger in both mirror conditions in later reading measures (gaze duration, go-past time, total reading time) and particularly pronounced in the horizontal condition. This indicates that reading mirrored script involves a late checking mechanism that is particularly important for reading horizontally mirrored script. Together, our findings demonstrate that mirroring affects both early visual identification and later linguistic processes.

3.2 Introduction

Reading is a complex cognitive activity that involves both visual and language-related processes. During this process, letters have to be discriminated and mapped onto words. However, letters are rather unique visual stimuli that differ in many ways from other perceptual objects. On the one hand, the letter identification system has to be flexible so that visual objects which vary in size, position, or shape are recognized as instances of the same entity (e.g. "a", "A", "*a*", "A", "**a**"). On the other hand, the system has to be sensitive enough in order to register even small discrepancies between letters, e.g. the difference between the letter "c" and "e" (Dehaene et al., 2005; Grainger et al., 2008). The question how humans accomplish this remarkable task is still unresolved. To answer this question, investigating how people read mirrored script, i.e. letters that are presented upside down or flipped around their vertical axis, is particularly informative. In the natural world, most objects are usually perceived as the same irrespective of the observer's viewpoint (Corballis & Beale, 1976). Letters, as human-made artifacts, are different though. Although most ancient alphabets had flexible reading directions, the lower case letters of the Latin alphabet were designed to be read from left-to-right and from the top to the bottom of a page (Wallace, 2011). As a consequence, some letters, most notably "b", "d", "p", and "q", receive radical different interpretations although they have the same shape and differ mainly in their orientation. Dehaene et al. (2005) suggested that efficient reading requires the suppression of mirror-invariance which is present in other perceptual domains.

Although mirror-invariance and mirror-image confusions can be a special impediment in reading alphabetic script, studies investigating readers' eye-movement behaviour during the reading of mirrored text are still scarce (but see Chandra et al., 2020; Kowler & Anton, 1987). In particular, the cognitive mechanisms underlying reading text with mirrored letters are still unknown and it remains unclear which processes are affected by mirroring. To address this question, we conducted an eye-tracking experiment in which adults read the Potsdam Sentence Corpus (Kliegl et al., 2004), a well-researched eye-tracking corpus in which target words are manipulated according to their length and frequency. Participants read the sentences in three different mirror conditions, a normal condition and two mirror conditions in which individual letters were either mirrored around their vertical (left-right) or horizontal (up-down) axis. We were especially interested in the effect of mirroring on participants' word length and frequency effects. In particular, we wanted to see whether the effects of word length and frequency would interact with mirror condition in order to determine which stage of the word recognition process is affected by mirroring (Staub, 2020).

The time that a reader spends processing a sentence or word reflects the ease with which text is processed. It is well established that both linguistic and visual variables affect how readers navigate their eye movements when reading connected text (Liversedge & Findlay, 2000; Rayner 2009, 1998; Rayner & Duffy, 1986). The two most prominent linguistic variables are word frequency and predictability. Words that occur more frequently in a language are processed faster and skipped more frequently (Inhoff & Rayner, 1986; Kliegl et al., 2006; Rayner & Duffy, 1986). Similarly, reading times are longer on a word that is unpredictable given its preceding context (Altarriba et al., 1996; Balota et al., 1985; Rayner et al., 2004). Both effects are benchmark findings in the eye-movement literature and demonstrate that reader's eye movements are tightly connected to the cognitive processes involved in language comprehension. As a consequence, they have both been incorporated in computational models of eye movements in reading such as E-Z Reader (Reichle et al., 1998, 1999) or SWIFT (Engbert et al., 2002).

Next to these language-related variables, a number of studies have investigated variables that are assumed to affect the visual processes involved in reading. These include contrast reduction (Staub, 2020; Sheridan & Reingold, 2013; White & Staub, 2012; Reingold & Rayner, 2006), font difficulty (Rayner et al., 2006; Staub, 2020), cAsE aLtErNaTiOn (Drieghe, 2008; Juhasz et al., 2006; Reingold & Rayner, 2006), or letter rotation (Blythe et al., 2019). These studies have shown that such visual manipulations make reading more difficult, although to varying degrees. For example, while the effects of contrast reduction are relatively subtle (increasing sentence reading times 5-20%; e.g. Warrington et al., 2018), letter rotations can have an massive impact on the reading process, especially if the rotation angle exceeds 60° and the rotation direction alternates between letters (which increases sentence reading times by ca. 300%; e.g. Blythe et al., 2019).

Surprisingly, although reading mirrored script has attracted a substantial amount of attention in cognitive science (Chandra et al., 2020; Rabe et al.,2021; Kowler & Anton, 1987) and neuroscience (Ryan & Schnyer, 2007; Poldrack & Gabrieli, 2001; Kassubek et al., 2001; Poldrack et al., 1998), studies investigating readers' eye movements while reading mirrored script are relatively scarce and have mainly focused on saccade targeting. For example, Kowler and Anton (1987) investigated the eye movements of two participants who read texts in which individual letters, words, or whole texts were either vertically or horizontally mirrored. They found that mirroring individual letters increased reading times dramatically from ca. 60 ms/letter during normal reading to ca. 240 ms/letter in the vertical mirror condition and ca. 460 ms/letter in the horizontal mirror condition. As the authors were mainly interested in the effects of mirroring on saccade programming, word reading times were not analyzed. However, the authors reported that mean saccade length was much smaller during the reading of mirrored text, indicating that words were decoded serially and less fluently.

This pattern is consistent with the results of several behavioral studies that have been conducted in the 1960s and 1970s. For example, in a seminal study Kolers (1968) investigated participants' reading speed as they read text in which either single letters or the whole text was vertically or horizontally mirrored. In addition, he also manipulated the reading direction (left-to-right, right-to-left). Findings showed that reading performance was mainly driven by an interaction of mirror condition and reading direction. Just focusing on the results in the left-right reading direction and mirroring individual letters, results showed that reading speed decreased from 220 words/min during normal reading to ca. 100 words/min in the vertical mirror condition and ca. 50 words/min in the horizontal reading condition.

In a recent eye-movement study, Chandra et al. (2020) investigated various eye-movement measures during reading of vertically mirrored text. They particularly focused on the impact on oculomotor processes and the eyes' landing positions. Participants read texts in a normal reading condition as well as when the individual letters and/or the entire words were written from right-to-left. For the letter condition, they reported that mirroring increased mean fixation duration from ca. 250 ms to ca. 300 ms. They also found that vertical mirroring decreased the proportion of skippings (from 30 to 13%) and regressive saccades (from 12 to 7%) and increased the number of refixations (from 23 to 30%). Similar to Kowler and Anton (1987) they found that forward saccade length was shorter in mirrored reading and the distribution of initial landing positions was shifted to the beginning of the word. Unfortunately, Chandra et al. (2020) did not include a horizontal mirror condition in their experiment. In addition, they did not investigate word length and frequency effects.

In sum, previous studies suggest that reading mirrored text substantially slows down reading and that vertical mirroring is less disruptive than horizontal mirroring. The main reason for this slow down is that parallel word identification breaks down and readers employ a serial processing strategy that impedes the reading process.

If mirrored text is read more serially, one would expect that mirroring interacts with word length. If the letters in a word are processed individually from left to right, reading times should increase linearly with the number of letters in a word. Word length effects are a marker effect for the influence of serial, attention-demanding letter-by-letter processing (e.g. Perry & Ziegler, 2002). This view is supported by the findings from single-word recognition studies that have investigated the effect of mirroring using the naming or the lexical decision task. For example, Björnström et al. (2014) investigated word-length effects when participants read aloud words of various lengths that were presented normally or, among other conditions, horizontally mirrored. They found that word length effects increased substantially from ca. 13 ms/letter to ca. 550 ms/letter. A similar interaction between word length and presentation mode has also been reported for rotated text by Navon (1978).

Indeed, adults reading mirrored text show a similar reading pattern as beginning or less-skilled readers. This is the reason why mirror reading has been used in many learning studies (Kolers, 1968; Kolers & Perkins, 1975; Kolers, 1976; Poldrack et al., 1998; Kassubek et al., 2001). In these studies, adults who are highly proficient in reading normal text learn to read mirrored text. As elaborated above, this is initially very demanding, but the reading process quickly becomes more automatic with increasing training. For example, Kolers and Perkins (1975) showed that readers were able to read horizontally mirrored text with near-normal speed after having read ca. 100 pages of mirrored text. Similarly, fMRI studies show structural changes in reading-related brain regions even after one training session (Poldrack et al., 1998). The learning curve follows a standard power function (Newell & Rosenbloom, 1993) indicating that letter identification becomes increasingly more parallel during training (Logan, 1988).

While it is clear that reading mirrored text is more resource demanding, it is not entirely clear why this is the case. Possible mechanisms are that mirrored letters consist of visual features that are less frequent or familiar to the reader or that these features are combined differently in mirrored letters. As a consequence, new feature-letter mappings have to be established. In terms of the interactive-activation model of visual word recognition (McClelland, 1979), mirroring effects are likely to occur on the feature-level or involve feature-to-letter mappings. This view is consistent with the Local Combination Detector (LCD) model that has been proposed by Dehaene et al. (2005). The model assumes a hierarchy of neural populations in the occipito-temporal visual pathway in which basic visual elements are successively combined into higher perceptual units and increasingly larger fragments of a word. Within this model, mirroring most likely affects the connections between local letter features (which are processed in V2), case-specific letter shapes (which are processed in V4), and a bank of abstract letter detectors (located at V8). In line with this model, fMRI studies show strong associations between mirror reading and activity in the so called visual word form area (VWFA) within the left occipito-temporal cortex (Cohen et al., 2008; Poldrack et al., 1998).

Another question which remains unresolved is why horizontal mirroring slows down the reading process more than vertical mirroring. One possible explanation is that vertical and horizontal mirror reading rely upon different cognitive mechanisms. This view is supported by an fMRI study of Zhao et al. (2010) who showed that reading horizontally mirrored compared to upright Chinese characters shifted the fMRI response from the VWFA towards regions involved in generic objects processing. Similarly, the processing of vertically mirrored letters (i.e. $< b >$ vs. $< d >$) is likely to differ from the effects of other very similar visual transformations such as plane rotations (i.e. $< b >$ vs. $< q >$) because vertical mirror-image discrimination and the discrimination of rotated images have been found to rely upon selective cognitive processes and anatomical networks (Logothetis & Pauls, 1995; Martinaud et al., 2016).

Within the letters of the Latin alphabet, there are several distinctive features which have been identified as being crucial for letter identification. These features include terminations, straight lines, curved lines, oblique lines, and intersections (Fiset et al., 2008; Gibson, 1969; Briggs & Hocevar, 1975). Curved lines are found in many letters and they are mostly oriented vertically (i.e. $< a >$, $< b >$, $< c >$, $< d >$, $< e >$, $< g >$, $< p >$, $< q >$) whereas downward or upward oriented curved lines are rather rare (i.e. $< u >$, $< n >$, $< m >$). Vertical mirroring thus likely disrupts the recognition of particularly those letters which comprise vertically oriented curved lines. By contrast, horizontal mirroring likely disrupts the recognition of letters which comprise ascending or descending straight lines for which the up-down orientation is a diagnostic feature (i.e. $< b >$, $< d >$, $< f >$, $< g >$, $< h >$, $< j >$, $< p >$, $< q >$, $< t >$). Given that there are about as many letters with vertically oriented curved lines as there are letters with ascending and descending straight lines, some degree of left-right mirror-invariance may account for why vertically mirrored text is easier to read than horizontally mirrored text (e.g. Dehaene et al., 2005; Rollenhagen & Olson, 2000; Corballis & Beale, 1976). However, it is also plausible to believe that in the horizontal mirror-condition, interference effects are stronger because there are more letters which are prone to be mirror-confused with a different normal letter when mirrored horizontally (i.e. $< b >$,$< d >$,$< p >$,$< q >$,$< n >$,$< u >$,$< w >$) as compared to when mirrored vertically (i.e. $< b >$,$< d >$,$< p >$,$< q >$) (we come back to this point in the discussion section).

While it is plausible that mirroring affects early visual letter processing, it is less clear whether it also affects later language-mediated processes. In order to investigate this question we also examined the effects of mirroring on frequency effects which are a marker effect of lexical processing (Rayner, 2009). According to Sternberg's additive factors logic (Sternberg, 1969), two variables that have additive effects affect different stages of processing, whereas two variables that have interactive effects may affect at least one common stage of processing. Applying this logic to the present study, an interaction between mirroring and word frequency would support the assumption that mirroring affects lexical processing. However, if the two variables were to produce additive effects, this finding would support the interpretation that mirroring effects are confined to visual letter-processing.

The question whether mirroring and word frequency have additive or interactive effects has not yet been investigated empirically. However, there are many studies that have examined the interaction between word frequency and other visual variables (Rayner et al., 2006; Reingold et al., 2010; Sheridan & Reingold, 2013; Warrington et al., 2018; Staub, 2020; Liu et al., 2016; Jainta et al., 2017). The empirical picture is mixed, but most studies that manipulated stimulus quality via contrast reduction or blurring found additive effects (Staub, 2020). By contrast, manipulations that target letter-level processing such as font difficulty (Staub, 2020; Slattery & Rayner 2010), case alternation (Reingold et al., 2010), or letter rotation (Blythe et al., 2019) reported an interaction with word frequency. These interactions are typically stronger in later reading measures such as gaze duration or total reading time.

A plausible theoretical explanation (see Staub, 2020) for this difference is that manipulations such as contrast reduction affect the perceivability of the letter which is located at the feature level of activation-based models (McClelland & Rumelhart, 1981; Coltheart et al., 2001). By contrast, manipulations such as font difficulty or letter rotation affect the spatial configuration of letter features which is located on the letter-level (Pelli et al., 2006; Sanocki & Dyson, 2012). Thus, the observed pattern of effects indicates that processing on the feature level is thresholded, while processing on the letter-level directly cascades into linguistic processing on the word-level and increases word frequency effects. One potential mechanism would be that increased processing difficulty on the letter-level necessitates the use of a late

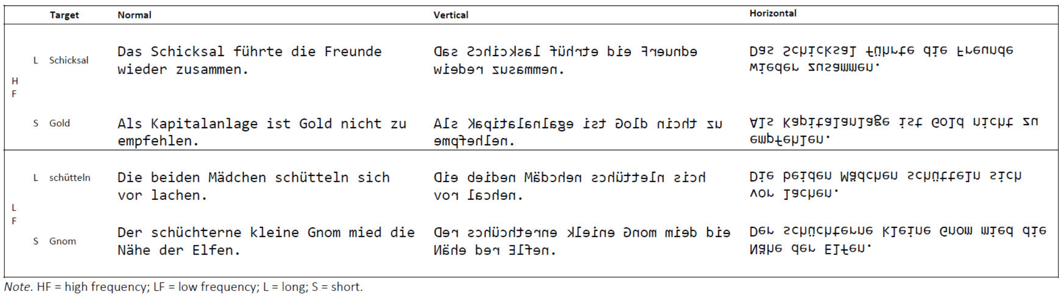


FIGURE 3.1: Example stimuli in each of the text presentation conditions.

checking mechanism in which readers use refixations or regression to resolve uncertainty about letter identity (Staub, 2020). As letter mirroring, similar to letter rotation and font difficulty, clearly changes the spatial configuration of letters features, it is plausible to believe that mirroring and word frequency would produce a similar pattern of interaction.

In the present study, we sought to investigate readers' eye movements while they were reading mirrored text. To do this, participants read sentences in which the individual letters of a word were either mirrored at their vertical (left-right) or horizontal (up-down) axis. Reading direction was kept intact and words were written from left-to-right (see Figure 3.1). Reading materials were the sentences of the Potsdam Sentence Corpus in which target words are orthogonally manipulated for word length and frequency (Kliegl et al., 2004, 2006). Based on previous findings (Kolers, 1968; Kowler & Anton, 1987; Chandra et al., 2020) we expected that both vertical and horizontal mirroring would substantially slow down reading and that horizontal mirroring would be particularly disruptive.

However, we also aimed at investigating the cognitive mechanism that underlies the mirroring effect. In particular, we were interested whether mirror effects are confined to visual processing or whether mirroring also affects lexical stages of the reading process. To address this question we investigated length and frequency effects and their interactions with mirror condition.

Based on previous single-word recognition studies (Björnström et al., 2014), we expected to see strong length effects in both vertical and horizontal mirrored reading. As horizontal mirroring is generally more disruptive, we also expected that length effects would be stronger here. An interaction between word length and mirror condition would indicate that mirroring effects are visually mediated and mirrored letters are perceptually normalized using a serial, attention-demanding mechanism.

Our predictions for the relationship between mirroring and frequency are less clear. First, it is not obvious whether frequency effects can be observed at all during mirrored reading. Mirroring might be so disruptive that the reading process breaks down completely and participants employ a general problem-solving mechanism that is independent of word frequency. However, given that participants are able to read mirrored text at near-normal reading speed after relatively short training periods, we thought this rather unlikely and expected to see frequency effects in later reading measures. Second, regarding the interaction between mirroring and word frequency, there are two alternative hypotheses. If the two variables have additive effects, this would indicate that mirroring mainly affects early visual processing and leaves lexical processing intact. If, by contrast, the two variables interact with each other, this would indicate that the processing difficulties caused by mirroring on the visual-perceptual level also permeate into later processing stages and interfere with lexical processing.

3.3 Methods

Participants We recruited 33 participants via the online recruitment system of the University Göttingen. The data of three participants had to be excluded from the analysis due to technical problems or poor data quality. The remaining 30 participants (age: M = 22, SD = 3 years, 25 women) were native German speakers, had normal or corrected vision, and no record of reading disability. Each individual participant had a performance rate that was $>$ 84%, indicating that participants read sentences accurately. The experiment was conducted in the laboratories of the Department of Educational Psychology and was approved by the ethics committee of the University of Göttingen.

Participants completed a standardized reading fluency subtest (the revised Salzburger Reading and Spelling Test SLRT-II, Moll & Landerl, 2010). Their percentile scores for the word reading subtest, M = 59.97, SD = 19.78, were slightly higher than the population mean, $t(29) = 2.76$, $p = .009$, whereas their scores on the nonword reading subtest, M = 53.97, SD = 25.27, were not, $t(29) = 0.86$, $p = .397$.

Results of a post hoc power analysis using the mixedPower package (Kumle et al., 2021) revealed that our sample size was adequate to detect with a power of .80 and an α-level of .05 main effects of about 20 ms (first fixation durations), 40 ms (gaze durations) and 51 ms (total reading time); two-way interactions of about 16 ms (first fixation durations), 35 ms (gaze durations) and 37 ms (total reading time) as well as three-way interactions of about 16 ms (first fixation durations), 31 ms (gaze durations) and 35 ms (total reading time).

Materials

The Potsdam Sentence Corpus We used the Potsdam Sentence Corpus (PSC) as stimulus materials (Kliegl et al., 2004). The PSC consists of 144 German sentences each comprising a target word that was manipulated according to word length and frequency. Frequent words were defined as words having lemma frequencies > 50 fpm (frequency per million) in the CELEX database (Baayen et al., 1995) and infrequent words were defined as words with lemma frequencies below 4 fpm. Word length was is divided into 2 categories: long words were 6-9 letters long and short words were 3-5 letters long. Carrier sentences represented a large variety of grammatical structures and the position of the target word ranged from the second to the last word in a sentence (mean target position was 4.9 words).

Mirror-Fonts We used the open source software Font Forge to create customized vertical and horizontal mirror-fonts that were based on the Consolas font. In the vertical mirror condition, letter bitmaps were mirrored at their vertical axis whereas in the horizontal condition letters were mirrored at their horizontal axis. For the horizontal font, bitmaps of individual letters were adjusted to a new baseline. This way we avoided changing the common spatial relationships between adjacent letters (i.e. not aligned: without alignment). To achieve the correct alignment, we flipped the entire virtual letter-space and created a new imaginary baseline to which the horizontally mirrored letters were aligned (i.e. aligned: with alignment).

Procedure The study had a 3(Mirror-condition: Normal vs. Vertical vs. Horizontal, within-participant, within-item) by 2(Frequency: High vs. Low, within-participant, between-item) by 2(Length: Long vs. Short, within-participant, between-items) design. Examples for sentences in all conditions are provided in Figure 1. Participants read the sentences silently while their eye-movements were being recorded. Each participant read one block in the vertical mirror condition, one block in the horizontal mirror condition and one block in the normal condition. The order of the three blocks was counterbalanced between participants. In each block, participants read one third of the sentences of the PSC. Sentences were divided into 3 item lists which were assigned to blocks and participants according to a Latin square design. Each sentence was only read once by each participant. The task of the participants was to read each sentence silently and answer a short comprehension question by pressing the corresponding key on the keyboard. Multiple choice questions were presented in normal font after 25% of the sentences. For example, the sentence "Even rapeseed can be used to produce fuel was followed by the question "What can fuel be made from?" with three response alternatives, "flax", "hemp", and "rapeseed".

Apparatus An EyeLink 1000 eye tracker (SR Research, Ontario, Canada) was used to record eye-movements during reading at a rate of 1000 Hz. Stimuli sentences were presented on a 2100 ASUS LCD monitor, with a refresh rate of 120 Hz. Participants sat at a viewing distance of 65 cm with an assisting head and chin rest to reduce head movements. Sentences were presented in the customized Mirror-Consolas font in black, size 18pt, on a white background using the UMass Eye Track 7.10 m software (Stracuzzi & Kinsey, 2006). Participants used a gamepad to indicate the end of each trial and to provide multiple choice responses to comprehension questions.

3.4 Results

In a first step, data were cleaned using the popEye package in R (Schroeder, 2019). During pre-processing trials were removed with insufficient calibration quality or too few fixations as well as trials in which a blink occurred directly before or after the target word. In this step, 13.6% of the data were excluded. In addition, we excluded trials with more than 10 runs or 80 fixations. In this step, an additional 3% of the data were excluded.

Data were analysed using generalized linear mixed-effects models with participants and items as crossed random intercepts. Mirror condition was included as a fixed effect in the model and was contrast-coded. For the local measures, word length and frequency were additionally included in the model as contrast-coded fixed effects. The significance of the factors was determined using type III Wald χ^2 tests using the Anova function of the car package (Fox & Weisberg, 2018). Where necessary post-hoc comparisons were conducted using cell means coding and custom-designed contrasts using the *glht* function in the *multcomp* package (Hothorn et al., 2008).

All duration measures were log-transformed prior to the analysis, but back-transformed in order to ease interpretation. In addition, of the log transformed measures, we excluded all observations deviating more than 2 *SD*s from the person or item mean before the analysis of each measure (excluding 1-1.1% of the data). The results are independent of the specific outlier criterion used for outlier cleaning.

Global analyses To examine the effects of mirroring on eye-movements on the sentence level we computed average skipping, refixation, and regression probability as well as the number of fixations made on the sentence, mean fixation duration, mean saccade length, firstpass reading duration, rereading time, total reading time, and reading rate. Descriptive statistics and the results from the corresponding linear mixed effects models are shown in Table 3.1.

Results showed a main effect of mirror condition on all global eye-movements measures. Post hoc contrasts between the normal and the vertical condition revealed a significant increase in re-fixation probability (SE = 0.006, z = 51.11, $p < .001$), regression probability (SE = 0.005, z = 7.451, $p < .001$), number of fixations (SE = 0.012, z = 61.76, $p < .001$), mean fixation duration (SE = 0.005, z = 60.51, $p < .001$), firstpass duration (SE = 0.012, z = 76.14, $p < .001$), re-reading time (SE = 0.125, z = 18.43, $p < .001$) and total sentence reading time (SE = 0.013, z = 78.73, $p < .001$). By contrast, mean saccade length (SE = 0.007, z = -66.33, $p < .001$), skipping probability (SE = 0.003, z = -32.29, $p < .001$) and reading rate (SE = 0.013, z = -79.18, $p < .001$) were lower in the vertical than in the normal condition.

Furthermore, reading times differed significantly between the horizontal and the vertical condition for re-fixation probability (SE = 0.006, z = 31.37, $p < .001$), regression probability (SE = 0.005, z = 4.469, $p < .001$), number of fixations (SE = 0.012, z = 49.04, $p < .001$), mean fixation duration (SE = 0.005, z = 35.74, $p < .001$), firstpass duration (SE = 0.012, z = 56.46, $p < .001$), re-reading time (SE = 0.127, z = 9.283, $p < .001$) and total sentence reading time (SE = 0.014, z = 55.86, $p < .001$), Again, this pattern was reversed for saccade length (SE = 0.007, z = -50.45, $p < .001$), reading rate (SE = 0.014, z = -55.63, $p < .001$) and skipping probability (SE = 0.003, z = -14.781, $p < .001$).

In sum, in line with previous findings, reading in both mirror conditions was more difficult than in the normal condition. Reading the sentences in the PSC in the normal condition took about 1.7 seconds, in the vertical mirror condition about 5 seconds, and in the horizontal condition about 10 seconds. Also in line with previous studies, reading in the horizontal condition took approximately twice as long than in the vertical mirror-condition. Similar effect sizes have been reported by Kolers (1968). However, effects are substantially smaller than the effects reported by Kowler and Anton (1987). Beyond replicating the overall effects of mirroring on total reading time, our findings show that mirroring has both immediate (skipping probability, mean fixation duration, firstpass reading time) and delayed effects (regression rate, re-reading time, regression probability). We will come back to this finding in the discussion section.

Local analyses To examine the effects of horizontal and vertical mirroring on the target words which were manipulated according to word length and frequency, we computed five dependent measures: first fixation duration, gaze duration, go-past time, and total reading time. Descriptive statistics for all measures are provided in Table 3.2. The results of the corresponding linear mixed effects models are reported in Table 3.3 and depicted in Figure 3.2. Prior to the analysis we excluded all target words with more than 14 fixations or that were

TABLE 3.1: Model Estimates for Sentence Reading Measures in the Normal, Vertical and Horizontal Condition and Results from Linear Mixed Effects Models Testing the Effect of Mirror Condition.

	Normal		Vertical		Horizontal			
	M	*SE*	*M*	*SE*	*M*	*SE*	$\chi^2(1)$	*p*
Skipping probability (%)	19.13[a]	0.79	8.70[b]	0.78	4.15[c]	0.78	2105.58	< 0.001***
Refixation probability (%)	20.13[a]	1.36	50.91[b]	1.35	69.98[c]	1.36	6501.1	<0.001***
Regression probability (%)	9.87[a]	1.09	13.33[b]	1.09	15.47[c]	1.09	137.52	<0.001***
Number of fixations (n)	8.10[a]	0.25	17.12[b]	0.54	31.18[c]	.98	11713.2	< 0.001***
Mean Fixation Duration (ms)	215[a]	4	294[b]	6	355[c]	7	8796.6	< .001***
Saccade length (n letters)	6.85[a]	0.21	4.26[b]	0.13	2.95[c]	0.09	12752.0	< 0.001***
Firstpass duration (ms)	1575[a]	69	3941[b]	172	3941[c]	346	16461	< .001***
Re-reading time (ms)	8[a]	2	82[b]	17	266[c]	55	756.14	< 0.001***
Total sentence reading time (ms)	1746[a]	75	5040[b]	2016	10827[c]	465	17071	< 0.001***
Reading rate (words/min)	267.18[a]	11.11	92.71[b]	3.84	43.47[c]	1.81	17109	< 0.001***

Note. Different letters indicates significant contrast.

TABLE 3.2: Model Estimates for First Fixation Duration, Gaze Duration, Go-past Time and Total Reading Time (Milliseconds) to Target Words (SEs in Parentheses)

		Normal		Vertical		Horizontal	
	Frequency	Long	Short	Long	Short	Long	Short
First fixation duration	HF	222 (8)	196 (7)	306 (10)	284 (9)	346 (18)	350 (18)
	LF	226 (8)	210 (7)	289 (15)	275 (14)	314 (16)	299 (15)
Gaze Duration	HF	230 (9)	204 (8)	516 (20)	380 (15)	1124 (121)	767 (83)
	LF	264 (10)	237 (9)	844 (91)	567 (61)	1795 (189)	1370 (147)
Go-past Time	HF	247 (12)	214 (11)	629 (31)	408 (20)	1354 (131)	916 (89)
	LF	270 (13)	246 (12)	927 (89)	641 (62)	1920 (185)	1566 (149)
Total Reading Time	HF	265 (12)	225 (11)	798 (37)	496 (23)	1568 (126)	954 (77)
	LF	302 (14)	257 (12)	1078 (87)	704 (57)	2130 (172)	1607 (128)

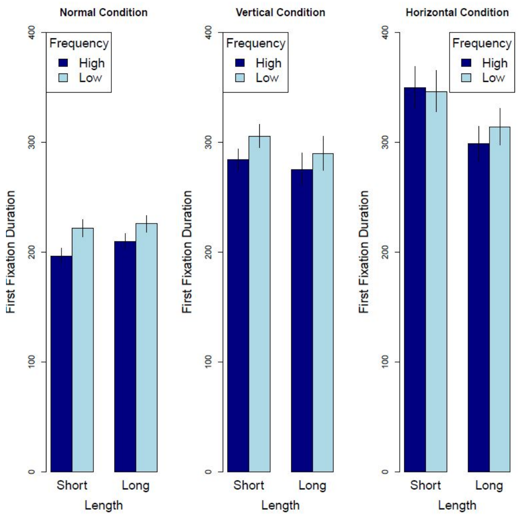
Note. HF = high frequency; LW = low frequency.

TABLE 3.3: Results from Linear Mixed-Effects Models (χ^2 Wald tests) for First Fixation Duration, Gaze Duration, Go-past Time and Total Reading Time

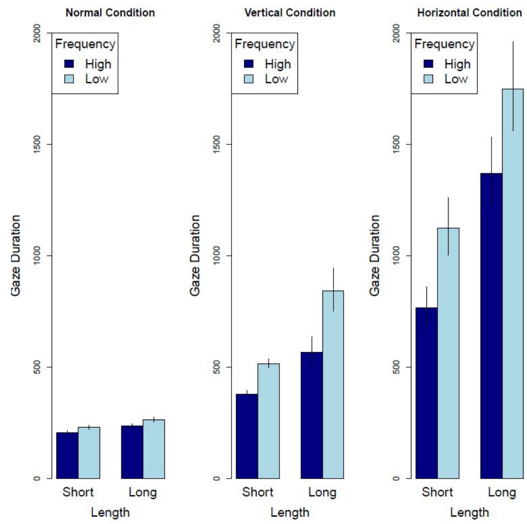
	FFD	GD	GPT	TRT
Intercept	98225.94***	32198.03***	26492***	27755.61***
Mirror-condition	447.72***	282.48***	394.09***	549.55***
Length	8.03***	112.77***	49.01***	26.92***
Length x Mirror-condition	18.44***	39.20***	31.86***	22.37***
Frequency	16.28***	31.36***	31.13***	33.43***
Frequency x Mirror-condition	1.92	17.62***	17.14***	16.67***
Length x Frequency	0.02	0.08	1.56	0.58
Length x Frequency x Mirror-condition	2.40	2.85	3.95	2.16

Note. * = $p < .05$, ** = $p < .01$, *** = $p < .001$. FFD = first fixation duration; GD = gaze duration; GPT = go-past time; TRT = total reading time.

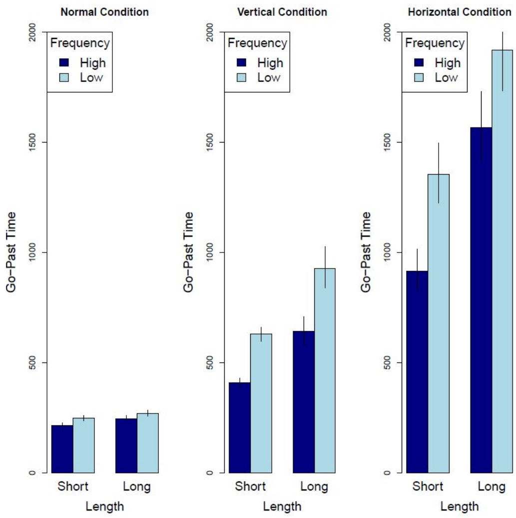
reread for more than 4 times (excluding ca. 1.7% of the data). In addition, we removed outlying observations deviating more 2 *SD*s from the person or item mean before the analysis of each measure (excluding 1-6% of the data).



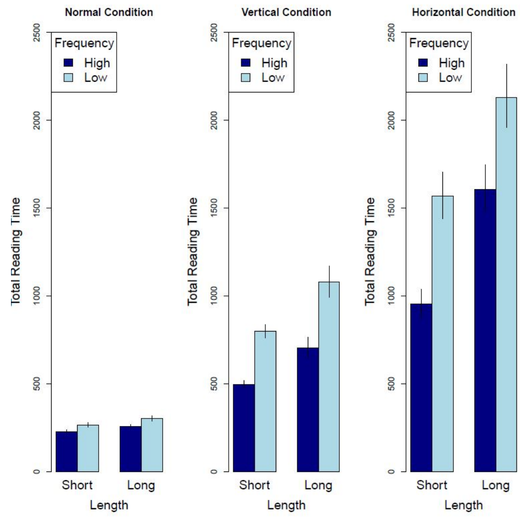
(a) First Fixation Duration



(b) Gaze Duration



(c) Go-past Time



(d) Total Reading Time

FIGURE 3.2: Plots a-d: First Fixation Duration, Gaze Duration, Go-past Time and Total Reading Time.

First Fixation Duration There was a main effect of mirror condition: First fixation durations for words in the vertical condition, M = 288 ms, SE = 11 ms, were Δb = .303 (75 ms) longer z = 10.570, $p < .001$, than in the normal condition M = 213 ms, SE = 6 ms. Similarly, first fixation durations in the horizontal condition, M = 326 ms, SE = 14 m, were Δb = .427 (113 ms) longer than in the normal condition, z = 10.880, $p < .001$. The contrast between the horizontal and the vertical condition was also significant, z = 4.153, $p < .001$.

Furthermore, there was main effect of length. First fixation durations for short words, M = 278 ms, SE = 11 ms, were Δb = -0.043 (12 ms) longer, z = -2.707, p = .006, than for long words, M = 266 ms, SE = 9 ms. In addition, the interaction between word length and mirror condition was significant, indicating that length effects were more pronounced in the two mirror-conditions than in the normal condition. In particular, the length effect in the normal condition, Δb = .042 (9 ms), z = 2.195, p = .028, was significantly smaller, z = -3.001, p = .002, than the length effect in the vertical condition, Δb = -0.043 (13 ms), z = -1.981, p = .048, and also significantly smaller, z = -4.364, $p < .001$, than the length effect in the horizontal condition Δb = -0.128 (42 ms), z = -3.819, $p < .001$. The length effects in the vertical and horizontal condition differed significantly from each other, z = 2.373, p = .018.

Notice that length effects in the two mirror-conditions were inverted, i.e. short words were processed *slower* than long words, while shorter words in the normal condition were processed faster than long words. The inverted length effects can be explained by a trade-off between first fixation duration and refixation probability. That is participants were much more likely to refixate words in the two mirror conditions (see Table 3.1), but, as a consequence, each of the individual fixations was shorter.

There was also a main effect of frequency: First fixation durations for frequent words M = 264 ms, SE = 9 ms, were Δb = -0.060 (16 ms) shorter than for infrequent words, M = 280 ms, SE = 9 ms. The interaction term for frequency and mirror condition was not significant.

Gaze Duration There was a main effect of mirror condition: Gaze durations for words in the normal condition M = 233 ms, SE = 7 ms, were Δb = .866 (320 ms) shorter than gaze durations for words in the vertical condition, M = 553 ms, SE = 39 ms, z = 15.99, $p < .001$, which were in turn Δb = .773 (646 ms) shorter than in the horizontal condition, M = 1199 ms, SE = 110, z = 12.27, $p < .001$.

Furthermore, there was a main effect of length. Gaze durations for short words M = 447 ms, SE = 32 ms, were Δb = .367 (197 ms) shorter than for long words, M = 644 ms, SE = 40 ms. In addition, the interaction between word length and mirror condition was significant, indicating that length effects were more pronounced in the two mirror-conditions than in the normal condition: In the normal condition, the length effect Δb = .143 (40 ms), z = 4.786,

$p < .001$, was significantly shorter, z = 5.003, $p < .001$, than the length effect in the vertical condition, Δb = .447 (249 ms), z = 6.732, $p < .001$ and also significantly shorter, z = 5.646, $p < .001$, than the length effect in the horizontal condition, Δb = .511 (620 ms), z = 7.230, $p < .001$. The length effects in the horizontal and the vertical condition did not differ significantly from each other, z = -0.826, p = .409.

There was a main effect of frequency. Gaze durations for frequent words M = 471 ms, SE = 29 ms, were Δb = -.260 (138 ms) shorter than gaze durations for infrequent words, M = 611 ms, SE = 38 ms, z = -6.002, $p < .001$. The interaction of frequency and mirror condition was also significant: The simple frequency effect in the normal condition, Δb = -0.114 (26 ms), z = -3.836, $p < .001$, was substantially smaller, z = 5.607, $p < .001$, than the simple frequency effect in the vertical condition, Δb = -0.352 (195 ms), z = -5.301, $p < .001$, and substantially smaller, z = 4.924, $p < .001$, than the frequency effect in the horizontal condition, Δb = -0.313 (377 ms), z = -4.427, $p < .001$; In addition, the frequency effect in the vertical mirror condition was significantly smaller than in the horizontal mirror condition, Δb = .664 (182 ms), z = 5.899, $p < .001$, indicating that frequency effects were more pronounced in the horizontal compared to the vertical mirror condition.

Go-past Time There was a main effect of mirror condition: Go-past time for words in the normal condition M = 243 ms, SE = 10 ms, was Δb = .943 (382 ms) shorter than go-past time for words in the vertical condition, M = 625 ms, SE = 51 ms, z = 17.55, $p < .001$, which in turn was Δb = .799 (765 ms) shorter than in the horizontal condition, M = 1390 ms, SE = 97, z = 16.48, $p < .001$.

Furthermore, there was a main effect of length. Go-past time for short words M = 506 ms, SE = 39 ms, was Δb = .326 (195 ms) shorter than for long words, M = 701 ms, SE = 46 ms. In addition, the interaction between word length and mirror condition was significant, indicating that length effects were more pronounced in the two mirror-conditions than in the normal condition: In the normal condition, the length effect Δb = .115 (28 ms), z = 3.666, $p < .001$, was significantly shorter, z = 4.633, $p < .001$, than the length effect in the vertical mirror condition, Δb = .421 (265 ms), z = 5.691, $p < .001$, and also significantly shorter, z = 4.586, $p < .001$, than the length effect in the horizontal mirror condition, Δb = .443 (621 ms), z = 5.423, $p < .001$. The length effects in the horizontal and the vertical condition did not differ significantly from each other, z = -0.323, p = .746.

There was a main effect of frequency. Go-past time for frequent words M = 520 ms, SE = 34 ms, were Δb = -0.272 (162 ms) shorter than go-past time for infrequent words, M = 682 ms, SE = 45 ms, z = -5.17, $p < .001$. The interaction of frequency and mirror condition was also significant: The simple frequency effect in the normal condition, Δb = -0.119 (29 ms), z

= -3.812, $p < .001$, was substantially smaller, z = 5.629, $p < .001$, than the simple frequency effect in the vertical condition, Δb = -0.401 (253 ms), z = -5.423, $p < .001$, and substantially smaller, z = 4.127, $p < .001$, than the simple frequency effect in the horizontal condition, Δb = -0.297 (414 ms), z = -3.641, $p < .001$; In addition, the frequency effect in the vertical condition was significantly smaller than in the horizontal mirror condition, Δb = .699 (161 ms), z = 5.014, $p < .001$, indicating that frequency effects were more pronounced in the horizontal compared to the vertical mirror condition.

Total Reading Time There was a main effect of mirror condition: Total reading time for words in the normal condition M = 261 ms, SE = 9 ms, was Δb = 1.043 (479 ms) shorter than total reading time for words in the vertical condition, M = 740 ms, SE = 40 ms, z = 24.73, $p < .001$, which in turn was Δb = .709 (764 ms) shorter than total reading time in the horizontal condition, M = 1504 ms, SE = 83, z = 16.1, $p < .001$.

Furthermore, there was a main effect of length. Total reading time for short words M = 573 ms, SE = 32 ms, was Δb = .290 (193 ms) shorter than total reading time for long words, M = 766 ms, SE = 37 ms. In addition, the interaction between word length and mirror condition was significant, indicating that length effects were more pronounced in the two mirror conditions than in the normal condition: In the normal condition, the length effect Δb = .131 (34 ms), z = 3.599, $p < .001$, was significantly shorter, z = 2.807, p = .005, than the length effect in the vertical mirror condition Δb = .325 (242 ms), z = 4.112, $p < .001$, and also significantly shorter, z = 4.626, $p < .001$, than the length effect in the horizontal mirror condition Δb = .414 (627 ms), z = 5.817 , $p < .001$. The length effect in the vertical mirror condition did not differ significantly from the length effect in the horizontal mirror condition, Δb = -0.089 (385 ms), z = -1.369, p = .171.

Furthermore, there was a main effect of frequency. Total reading time for frequent words M = 560 ms, SE = 27 ms, was Δb = -0.335 (46 ms) shorter than for infrequent words, M = 783 ms, SE = 38 ms, z = -6.323, $p < .001$. The interaction of frequency and mirror condition was also significant. The simple frequency effect in the normal condition, Δb = -0.163 (43 ms),z = -4.488, $p < .001$, was substantially smaller, z = 6.034, $p < .001$, than the simple frequency effect in the vertical mirror condition, Δb = -0.451 (337 ms), z = -5.704, $p < .001$, and the simple frequency effect in the horizontal mirror condition, Δb = -0.389 (589 ms), z = -5.467, $p < .001$; In addition, the frequency effect in the vertical condition was significantly smaller than in the horizontal mirror condition, Δb = .840 (252 ms), z = 6.190, $p < .001$, indicating that frequency effects were more pronounced in the horizontal compared to the vertical mirror condition.

3.5 Discussion

This study investigated the cognitive mechanism that underlie the reading of text with mirrored letters. To this end, we recorded the eye-movements of skilled adult readers as they read the Potsdam Sentence Corpus (PSC) (Kliegl et al., 2004). Individual letters were mirrored horizontally (around their up-down axis) or vertically (around their left-right axis). Each sentence of the PSC comprised a target word that is manipulated for length and frequency. We were particularly interested in length and frequency effects and their interaction with mirror condition. Our main findings are that reading horizontally mirrored text disrupted the reading process more than reading vertically mirrored text. In addition, mirror condition interacted with word length and word frequency. Below we elaborate on our key findings and explain their theoretical implications.

First, we found that reading mirrored text substantially slows down the reading process. Based on past research with mirrored text (Kolers, 1968; Kowler & Anton, 1987; Chandra et al., 2020) we expected that sentences with vertically mirrored letters would produce less disruption in both global and local eye movement measures relative to sentences with horizontally mirrored letters. This expectation was confirmed for all early and late measures examined in this study. Based on previous mirror reading studies with vertically and horizontally mirrored text, we expected vertical mirroring to be less disruptive than horizontal mirroring (Kolers, 1968).

Furthermore, past studies from single-word recognition have shown that reading words with mirrored letters substantially increases word length effects (Björnström et al., 2014). Thus, we expected 1) that word length effects in both mirror conditions would be more pronounced than in the normal condition and 2) that the size of the word length effect would be larger in the horizontal than in the vertical mirror condition. The first hypothesis was confirmed. We found that length effects were significantly more pronounced in each mirror-condition compared to the normal condition for all late eye-movement measures in the local analysis of the target words: gaze duration, go-past time and total reading time. By contrast, the second hypothesis was not confirmed. Length effects were equally pronounced in both mirror-conditions. Our results are thus in line with the assumption that readers apply an attention demanding serial letter-by-letter decoding strategy in mirror reading (Cohen et al., 2008). This effect, however, is independent of the direction of mirroring. Overall, our results thus show that mirror reading is fundamentally similar to other kinds of visual manipulations which slow down reading by enforcing serial letter-by-letter encoding. It would be interesting to see whether similar interactions with word length would occur for other visual manipulations typically used in eye-tracking studies (stimulus degradation, font difficulty, letter rotation; Staub, 2020; Blythe et al., 2019).

Turning to the effects of word frequency, a first important finding is that we observed substantial frequency effects for both early (first fixation duration) and later (gaze duration, go-past time and total reading time) eye-movement measures. This indicates that language-related, lexical processes are intact during reading mirrored text and participants did not identify words using a general problem solving strategy that is unrelated to reading. Thus, participants read mirrored text more slowly, but they were still reading.

In addition, we found that mirroring and word frequency interacted in gaze duration, gopast time and total reading time, i.e., the size of the frequency effect was larger in both mirror conditions than in the normal condition. This pattern is similar to the findings of Staub (2020) who also reported interacting effects of word frequency and font difficulty manipulation for later reading measures. Similarly, Blythe et al. (2019) reported an interaction between letter rotation and word frequency for gaze duration and go-past time. Moreover, our findings indicate that frequency effects were larger in the horizontal than in the vertical mirror condition. This indicates that uncertainty about letter identity was higher in the horizontal condition and, as a consequence, it is more important to verify the correct lexical interpretation later in the reading process (Staub, 2020).

Turning to the theoretical implications of our findings, our results are informative about the relationship between the letter-level and the word-level of processing. Mirroring effects are similar to other visual manipulations such as font difficulty or letter rotation which are located on the letter level and which have previously been shown to produce interactive effects with word frequency. The interaction of mirroring and frequency indicates that difficulties in letter processing permeate to the word level where they produce the observed larger frequency effects. This supports the notion that processing is cascaded between the letter and the word-level. The finding that these interactions were only observed for later reading measures implicates some corrective process on the word-level, such as an additional checking mechanism during lexical verification.

In the present study we showed *when* mirroring affects the reading process. Further research will be required to address the question of *why* these interference effects occur. Potential mechanisms are:

1. Mirrored letters consist of visual features that are less frequent or familiar to the reader.
2. Letter features are combined differently in mirrored letters and, as a consequence, new feature-letter mappings have to be established.
3. Mirroring distorts supra-letter information such as word shape or frequently co-occurring feature combinations.

4. Mirror reading can create interference effects if the mirror image of a letter is similar to a different letter in normal orientation (e.g., "b" and "d").

These explanations are not mutually exclusive and mirror effects are likely to be a result of several mechanisms at the same time. In addition, the different mechanisms might contribute differentially to vertical and horizontal mirroring effects. For example, vertical mirroring is more likely to preserve word shape information than horizontal mirroring. In order to systematically investigate the various mechanisms, future research should manipulate these different features separately. Because in our study length and frequency were between item manipulations and our sample size might have been not sufficient to detect the triple interactions between length, frequency, and mirror condition, it would be helpful to replicate our findings using a within items design in a larger eye movement experiment. In addition, future studies should investigate how additionally changing the order of the letters in a word or mirroring the word as a whole ("word" vs. "drow") affects the reading process (e.g. Kolers, 1968; Chandra et al., 2020).

In conclusion, this study adds to the body of research exploring how letter mirroring affects the reading processes. We extend previous work on the mirroring effect which has primarily focused on reading on the text- or word-level. We recorded participants' eye movements while they read single sentences in which target words were manipulated according to their length and frequency. Furthermore, we extended previous eye-movement research on the mirroring effect in that we additionally included horizontally mirrored letters in our experimental design.

Our results show that on the sentence level, reading horizontally mirrored script is substantially more disruptive than reading vertically mirrored script. In addition, both mirror conditions did substantially increase word length effects compared to the normal condition, indicating that participants processed words more serially during mirror reading. However, frequency effects were observed in all reading measures showing that lexical processing was still intact. In addition, mirror condition and word frequency interacted which indicates that mirroring affected language related processes.

Chapter 4

Effects of Mirror-Confusability on Reading

Katharina Pittrich & Sascha Schroeder

4.1 Abstract

When letters are written vertically or horizontally mirrored, some letters (e.g p, d, p) are more likely to be confused with another mirror-written letter. We refer to the likelihood of letters and words to be confused when mirrored as mirror-confusability. In first step, based on data from a speeded visual letter identification task including vertically (left-right) and horizontally (up-down) mirrored letters, we developed a score which quantifies the mirror-confusability of all upper- a lower case letters of the Latin alphabet. In a second step, we used the letter-based score to compute word average confusability. Words were classified into high and low confusability words and used as target words in a lexical decision (Exp. 2) and an eye-tracking (Exp. 3) study in which words and sentences were either vertically or horizontally mirrored. We show that in the lexical decision task, mirror-confusability moderates word reading times. By contrast, during sentence reading, mirror-confusability moderates two later eye-movement measures (gaze durations and total reading time) in the horizontal but not the vertical condition. The results indicate that mirror-confusability is a visual variable which affects visual word recognition and eye-movements in functional reading adults.

4.2 Introduction

Children all over the world pass through a transitional stage where they mirror-confuse letters. These mirror-confusions occur in reading (Dehaene et al., 2010; Gardner & Broman, 1979; Fischer, Liberman, & Shankweiler, 1978) and writing (Portex et al., 2018; Fischer & Tazouti, 2012; Cubelli & Della Sala, 2009; Cornell, 1985; Aaron & Malatesha, 1974), and they occur both vertically (b vs d) and horizontally (b vs p). Interestingly, research suggests that even proficient adult readers produce mirror-confusions, although these are confined to an early, automatic and unconscious stage of the word recognition process (Fernandes et al., 2021; Soares et al., 2019; Perea et al., 2011; Duñabeitia et al., 2011). However, not all letters are similarly likely to be mirror-confused. In this study, we wanted to investigate how the letters' mirror-confusability affects visual word recognition. To this end, first we developed a score which quantifies the propensity of all upper- and lower case letters of the Latin alphabet to be subjected to vertical and horizontal mirror-confusions using data from a visual letter-identification task (Exp. 1). In second step, the score was used to compute the average confusability of a word. Words were categorized as either high- or low confusable and used in two reading tasks in which letters within words were either vertically or horizontally mirrored: a lexical decision task (Exp. 2) and a sentence reading task (Exp. 3) in which participants' eye-movements were monitored. We expected that letter confusability permeates to the word level an that high-confusable words are more difficult to read than low-confusable words.

There is a common consensus that orthographic processing is deeply rooted in the structure of the visual system. One central aspect of visual processing that is particularly relevant for reading is mirror-generalization (Bornstein et al., 1978; Logothetis & Pauls, 1995; Rollenhagen & Olson, 2000). Mirror-generalization refers to the tendency of the visual system to treat visual input and its mirror-image reversal equivalently. Generally, mirror-generalization is thought to enable viewpoint invariant object recognition (Corballis & Beale, 1976; Dehaene et al., 2005). The vast majority of writing systems include several symmetrical letters, of which more are symmetrical about their left-right (vertical) compared to their up-down (horizontal) mirror axis (Morin, 2018). Symmetry was also a predominant characteristic in ancient alphabets which had flexible reading directions. For example, in ancient Greek inscriptions from the 6th century B.C. and also scattered early Etruscan and Latin inscriptions, the lines of writing and the letters appeared to be reversed line by line (boustrophedon writing) (Haarmann, 1990). In these ancient scripts, orientation was not a diagnostic feature of letters. For reading alphabetical script, however, the orientation of letters is important (e.g. b vs d) and thus, mirror-generalization is detrimental to reading. The perception of letters is a highly complex process. On the one hand, readers have to be able to distinguish letters which differ only minimally (e.g. c vs e). On the other hand, readers must achieve translational and/or mirror-invariance (Perea et al., 2011) which, applied to letter recognition, means the ability to recognize "a", "A", "*a*", "A", "**ɑ**" as well as " ɐ " and " ɒ " as instances (or allographs) of the letter $< a >$. If words comprise reversible letters such as "b" or "d", treating these letters equivalently can lead to mirror-confusions in reading. While mirror-generalization is mostly associated with left-right (vertical) confusions (Dehaene et al., 2005; Corballis & Beale, 1976) it has been shown that mirror-confusions also occur across the up-down (horizontal) axis (e.g. b vs p) (Gregory, Landau, & McCloskey, 2011; Gregory & McCloskey, 2010).

Orientation is critical feature for differentiating letters in beginning readers (Gibson et al., 1962) and it is hypothesized that in proficient readers, mirror-generalization is unlearned (Dehaene et al., 2010; Pegado et al., 2011; Pegado et al., 2014a), suppressed (Lachmann, 2002), or inhibited (Ahr et al., 2016; Duñabeitia et al., 2011; Perea et al., 2011) during the processing of text. Indeed, non-proficient readers seem to process reversible letters differently than non-reversible letters. For example, Terepocki et al. (2002) compared 10 children with reading disability and ten children with normal reading ability in a series of tasks, including a reversal detection subtask. In the subtask, letters that were either reversible or non-reversible were embedded in 80 four-letter monosyllabic sight words. There were 16 target and 64 non-target items. The 16 target words each contained a letter which was either vertically or horizontally mirrored. Eight target words contained the non-reversible letters (j, e, y, c, r, k, h, a) presented in a mirror-transformation, resulting in a non-letter (e.g., ꓘite) while the other 8 target words contained the reversible letters (f, w, m, t, b, d, n, p) that were either vertically or horizontally mirrored in order to form another letter. None of the target words contained a reversible target letter that in modified orientation could form a new word (e.g., dake for bake was used instead of fake and take). Comparing the number of errors made on reversible letters (e.g., words containing b as the modified orientation of d) with the number of errors made on non-reversible letters (e.g., words containing the mirror-image of k), Terepocki could show participants made significantly more errors on reversible than on non-reversible items. Furthermore, the effect of item-reversibility was equally pronounced in both groups, indicating that reversibility effects on reading are not confined to groups who have a specific reading disorder.

Interestingly, it has been shown that even in functional reading adults, words which comprise reversible letters are processed differently than words which comprise only non-reversible letters, although in adults, these mirror-effects are confined to an early, automatic stage of the word recognition process. Such early, automatic processes are usually examined through the use of an orthographic masked mirror-priming experiment. In these experiments, a mirror-priming condition is created by using an identity prime (e.g., table-TABLE) in which individual letters are mirrored (e.g., tadle-TABLE). The rationale behind this is that if readers unconsciously mirror letters, then mirror-primes which comprise only non-reversible letters (e.g. r, k, s) should pre-activate the correct corresponding letter representation and produce mirror-priming effects on word recognition that are similar to the identity priming effect. If, by contrast, the mirror-primes comprise reversible letters (e.g. b, d, p) then the mirror-primes should pre-activate two competing letter representations (e.g. b activates b and d) and produce interference effects on target word recognition.

For example, Perea et al. (2011) and Soares et al. (2019) showed that only words which comprise reversible letters produce mirror interference effects on an early, automatic processes in visual word recognition. Besides the expected identity priming effects, both experiments found that target words with reversible letters were recognized significantly slower when the prime's critical letter was reversible letter as compared to a control condition with a no-reversible letter. Additionally, Soares and colleagues showed that the mirror-interference effects were confined to words comprising reversible, left-facing letters (d-words), indicating that the orientation of reversible letters is another features which moderates their confusability.

Perea and colleges additionally found that their control primes - in which the critical letter was non-reversible - produced mirror-priming effects that were as pronounced as the identity priming effect. Similar mirror-priming effects have been found by Duñabeitia et al. (2011) on a neuronal level and by Winskel and Perea (2018) on a behavioural level, although in the study of Winskel and Perea, mirror-priming effects equalled identity priming effects only in native readers of Thai (which does not comprise reversible letters) whereas in native readers of English, mirror-priming effects were less pronounced than the identity priming effect.

In summary, there is an implicit consensus in the literature that the letters of the Latin alphabet differ in their propensity to be confused with other letters when being mirrored. In addition, there is some agreements these differences have important consequences for visual word recognition. However, previous studies have mainly differentiated between reversible (e.g., b vs d) and non-reversible letters (e.g., r vs ɿ) and they have only considered vertical reversibility. None of the previous studies has systematically examined the mirror-confusability of the Latin alphabet and its impact on visual word recognition. The present study addresses three important questions: First, how can the confusability of the letters be quantified?. Second, how does letter confusability affect the identification of whole words when they are mirrored? And third, do effects of word confusability vary when words are embedded in context?

In order to answer these questions, in a first step, we developed a metric which quantifies the mirror-confusability of all upper- and lower case letters of the Latin alphabet. The metric takes into account not only letter-reversibility but also inter-letter-similarity when letters are being mirrored horizontally (up-down) and vertically (left-right). In a second step, we used the metric to quantify and manipulate the overall propensity of words to be mirror-confused (the word's mirror-confusability), in two tasks which involved the recognition of singly presented words and a more natural silent sentence reading. The aim of the current study was to quantify the mirror-confusability of the Latin alphabet and to examine whether a word's overall mirror-confusability moderates word reading times and eye-movements in adults. Furthermore, we wanted to see whether effects of confusability vary with task demands.

In a first step, we developed a metric which allows to quantify the mirror-confusability of words based on the confusability on their individual component letters. The metric was developed based on empirical data from a visual letter identification task with mirrored letters. In a second step, we performed two additional experiments in which participants performed a mirror-reading task. Text was presented with individual letters mirrored either horizontally or vertically and the mirror-confusability of target words was manipulated. In Experiment 2, participants performed a lexical decision task whereas in Experiment 3, the target words were embedded in sentences and participants' eye-movements were monitored.

4.3 Experiment 1

4.3.1 Introduction

Confusability is measure of similarity and there are different methods that are commonly used for evaluating inter-letter-similarity.

For example, a commonly method used to measure inter-letter-similarity is by asking participants to rate letter-similarity (e.g. Boles & Clifford, 1989; Podgorny & Garner, 1979), as well as analysing response times (Podgorny & Garner, 1979) or saccade times and accuracies (Jacobs et al., 1989) based on data from a same-different match task. Another method is a two-alternative forced choice letter identification task (Mueller & Weidemann, 2012) in which the participant is briefly presented with a letter which is often preceded and/or followed by a mask. After that, the participant is presented with two choices: the target, and an incorrect alternative of which she has to select the option was previously presented. This task, however, is somewhat different from reading because in everyday-reading, letters are matched against an internal representation of the letter in the readers mind rather than against a physically presented letter.

The most commonly used method to evaluate the inter-letter-similarity structure of the Latin alphabet is by creating letter confusion matrices. Typically, confusion matrices are coupled by letter identification or naming tasks. A confusion matrix is constructed by computing the number of times a letter was given as a response for another letter when presented in a letter-identification task. This captures the most common errors during letter identification. In a confusion matrix, errors presumably index the similarity between the presented letter and the participants' mental letter representation (Mueller & Weidemann, 2012) which is similar to the process that occurs during reading. In order to reduce naming accuracy and develop better estimates of letter similarity, the letters are presented under different types of stimulus degradation such as brief (Mueller & Weidemann, 2012), small (Phillips et al., 1983), peripheral (Reich & Bedell, 2000), as well as noisy or low contrast presentations (Liu & Arditi, 2001).

For example, Dawson and Harshman (1986) used confusion matrices to study letter recognition of upper-case letters under visual disruptions such as very short presentation, low spatial filtering or dot matrix presentation. They found that both within and across different visual transformation manipulations, letter confusions are asymmetric. "Asymmetric" means that a <Q>, for instance, is mistakenly reported as <O> much more often than <O> it is mistakenly reported as <Q>.

Despite their utility, confusion matrices have also several drawbacks. For example, many studies which have used confusion matrices to quantify inter-letter-similarity have merely focused on the upper-case letters (Uttal, 1969; Loomis, 1974; Gilmore, Hersh, Caramazza & Griffin , 1979; Gupta, Geyer & Maalouf, 1983) and the data is often incomplete because error rates are low. Furthermore, the method used to degrade the stimuli and increase error rates, influences the nature of the confusions (Grainger et al., 2008). According to Fiset et al. (2008), low contrast or rapid presentation can exacerbate the relative importance of low spatial frequencies and different types of degradation are known to produce different patterns of confusions (Grainger et al., 2008).

To overcome some of the above described limitations, Simpson et al. (2013) created a confusability matrix that is based on untimed responses to clearly presented upper- and lowercase letters of different Latin-based alphabets, including characters from Catalan, Dutch, English, French, Galician, German, Italian, Portuguese, and Spanish. Participants were asked to rate the letter pairs purely on visual similarity using a scale from 1 (not at all similar) to 7 (very similar).

One problem with such a confusability matrix based on normally presented letters is that it does not allow to isolate the mirror-confusability of letters. For example, the confusability matrix of Simpson and colleagues also comprises several letter pairs which received a high confusability rating because they are vertical (e.g., d vs b rated with 5.60) or horizontal (e.g., p vs b rated with 5.07 or t vs f rated with 4.80) mirror-images of each other. Or, because they can be transformed into each other by an 180° clockwise rotation (e.g., d vs p rated with 5.10) which corresponds to a simultaneous vertical and horizontal mirror-image reversal.

If an increase in inter-letter similarity is indeed the result of some class of implicit mirror-image reversal - based on general visual principles of mirror-generalization - then a confusability matrix in which letters are presented under different mirror-transformations isolate the mirror-confusability of the Latin alphabet. In other words, while a letter's symmetry can be defined as self-similarity under a class of mirror transformation, a letter's mirror-confusability can be defined as its inter-letter-similarity under a class of mirror transformation.

Unfortunately, previous research in which letters were mirrored is still scarce and has merely considered a small subset of letters. For example, Kolers and Perkins (1969a) conducted an experiment in which proficient adult readers named vertically (e.g. b/d) and horizontally (e.g. b/p) mirrored letters. Each page of material appeared in a single text transformation so that participants could deduce which type of mirroring was applied. The authors examined the confusions of eleven letters (i.e. s, a, b, d, g, p, q, n, u, f, t) and found that the frequency of errors of mistaking for example u/n and f/t was not the same for all kinds of text transformations. More importantly, mirroring letters horizontally induced the greatest percentage of errors whereas mirroring letters vertically induced fewer. Interestingly, participants tended to confuse letters mostly with their vertical mirror-image counterpart. If, for example, the letter $< d >$ was presented in the horizontal mirror-condition as $< q >$, the error type data revealed that $< q >$ was confused mostly with $< p >$, which corresponds to an implicit *vertical* mirror-image reversal. The latter indicates that implicit vertical mirror-image generalization may have caused a substantial proportion of the observed confusions errors.

In sum, previous studies have provided a first insight on the most common confusions errors within the Latin alphabet and on how vertical and horizontal mirror-image reversals affect the recognition of singly presented letters. However, studies which have elaborated confusion matrices for the Latin alphabet have not examined how specific mirror-image reversals increase inter-letter-similarities. By contrast, those studies which did examine how specific mirror-image reversals impact letter recognition, have merely focused on a small subset of letters. Furthermore, none of the previous studies has systematically quantified the mirror-confusability of the entire Latin alphabet by taking into account both confusion errors and reaction times. Both variables, however, need to be combined in a metric because both reflect difficulties in visual letter recognition.

The aim of Experiment 1 was to develop a metric which systematically quantifies the mirror-confusability of the entire Latin alphabet by considering both same-case and mixed-case inter-letter-similarities as well as possible asymmetries in these confusions. Participants performed a speeded letter-identification task in which upper- and lowercase letters were presented intermixed and either normally, mirrored vertically and mirrored horizontally. Response accuracy- and reaction times for all letters in three presentation conditions were recorded. Based on response accuracy and speed for each letter in each mirror-condition compared to the normal condition, we created a combined metric which quantifies the mirror-confusability of the entire Latin alphabet in each mirror-condition.

We expected letters to vary substantially in their degree of confusability. Based on the overall higher degree of symmetry in the upper-case letters, we expected the upper-case letters to have a lower mirror-confusability than the lower-case letters.

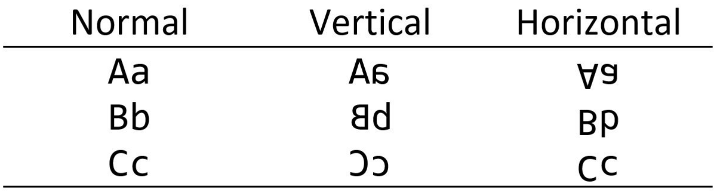
4.3.2 Methods

Participants We recruited adult participants via the Recruiting System of the University of Göttingen for an online-experiment in which 30 adults (age:M = 23, SD = 4, years; 21 female) participated. All participants were German speakers, had normal or corrected to normal vision, and had no record of reading disability. The study was approved by the Ethics Committee of the University of Göttingen. At the beginning of the study, participants provided informed consent electronically. Participants received course credit for participation.

Materials

Letter-targets We used the open source software Font Forge to create new customized vertical and horizontal mirror-fonts that were based on the Consolas font. In the vertical mirror-condition, letter bitmaps were mirrored around their vertical mirror-axis whereas in the horizontal mirror-condition letter bitmaps were mirrored around their horizontal mirror-axis. An example of the font used in the Normal, Vertical and Horizontal condition is shown in Figure 4.1.

FIGURE 4.1: Experiment 1: Example of the font used in the Normal, Vertical and Horizontal condition



Procedure Participants performed a visual letter identification task in which letters were presented in three conditions: normal, horizontal mirroring and vertical mirroring. First letters were presented in Normal Font whereas the vertical and the horizontal mirror-condition were counterbalanced. In each block participants completed 240 trials that were preceded by 15 practice trails. Letters were presented four times in randomized order within each experimental condition with upper- and lower case letters intermixed. The task of the participants was to identify each letter as fast and as accurate as possible by pressing the corresponding key on the keyboard. In order to respond to upper-case letters, a key press of the corresponding lower-case letters was required.

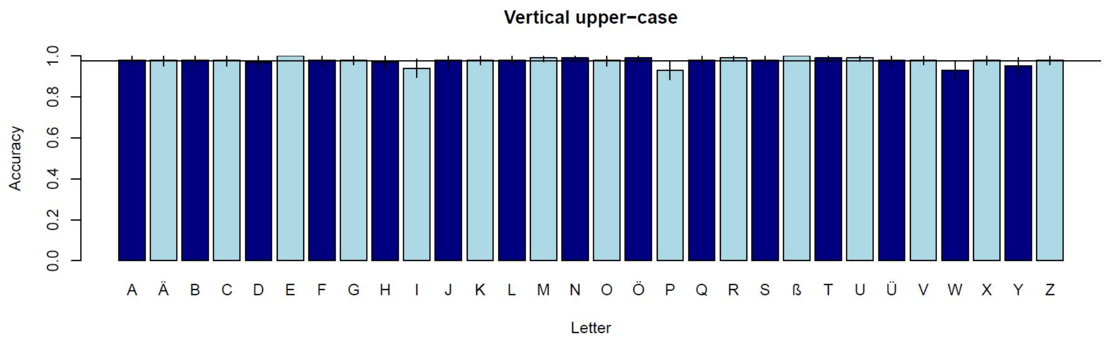
4.3.3 Results

Results were analysed using Linear Mixed Effects models using the lme4 package (Bates et al., 2015) for R (R Core Team, 2013). For response accuracy, a generalized linear mixed-effects model with a binomial link function was used. Inverse transformed response latencies were analysed using a Linear Mixed Effects model. The data was cleaned in two stages. First, outliers were deleted by excluding all trails that were extremely fast (<=300ms) or slow (>=3000ms). In this step, 0.7% of the trials were excluded. I the second step, we performed a model based outlier deletion with correction adjustment for subject intercepts. In this step, 2.3% of the trials were excluded. In each model we entered mirror-condition, letter-case and letter-identity as effect-coded fixed effects. To control for training effects we included trial-number additionally as a continuous effect but results are not reported here. As random effects, random intercepts for participants were specified. Overall effects were evaluated using Wald tests and the Anova function of the car package using type III model comparisons. If necessary, post-hoc comparisons were computed using cell means coding and customized contrasts using the multcomp package (Hothorn et al., 2008).

TABLE 4.1: Experiment 1: Results from the Linear Mixed-Effect Model for Response Accuracies und Latencies

	Accuracy		*RTs*	
Effect (df)	χ^2	p	χ^2	p
Mirror-condition (1)	0.00	1	2595.54	<0.001***
Letter (29)	78.78	< .001***	6797.32	< .001***
Case (1)	0.00	0.9912	382.22	< .001***
Mirror-condition x letter (58)	88.76	< .01**	2147.58	< .001***
Mirror-condition x case (2)	0.00	0.9999	241.07	< .001***
Letter x case (29)	77.44	< .001***	1866.19	< .001***
Mirror-condition x Letter x Case (58)	83.85	< 0.05*	1167.24	< .001***

FIGURE 4.2: Experiment 1: Response accuracy for upper-case letters in the vertical condition



Response accuracy Response accuracies are shown in Figure 4.2, 4.3, 4.4 and 4.5. Results from the linear mixed-effects model for response accuracy are shown in Table 4.1. Correct performance, averaged across items and participants was M = 95.6%, SD = 20.5%. First, we found a strong main effect of letter and an interaction between letter and case, indicating that there were strong overall differences in response performance to specific upper- and lower case letters. For upper-case letters, response accuracy was near ceiling for most letters while response accuracy varied substantially for lower-case letters. More importantly, there was a strong interaction between mirror-condition and letter indicating that individual letters were affected differently by vertical and horizontal mirroring. Overall, response performance was much lower in the Horizontal than in the Vertical condition. As expected, the letters $< b >$,$< d >$,$< q >$,$< p >$,$< n >$,$< u >$ were more severely affected by mirroring, however, also letters like $< f >$,$< t >$,$< w >$,$< m >$,$< l >$ decreased substantially in accuracy.

FIGURE 4.3: Experiment 1: Response accuracy for lower-case letters in the vertical condition

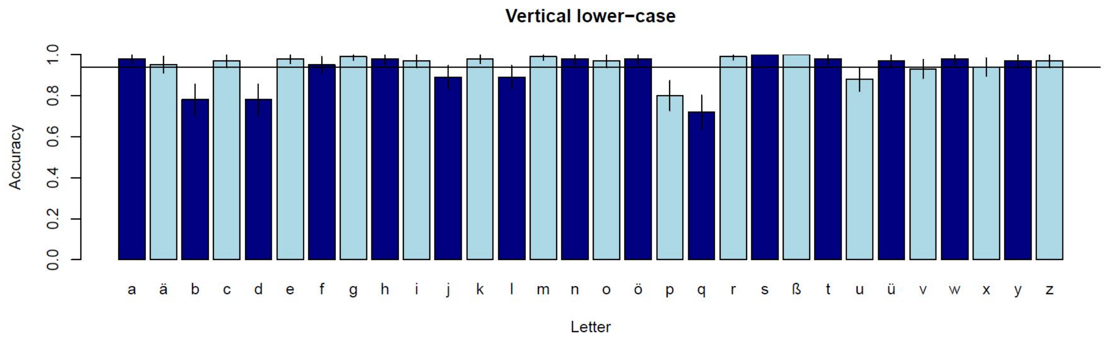


FIGURE 4.4: Experiment 1: Response accuracy for upper-case letters in the horizontal condition

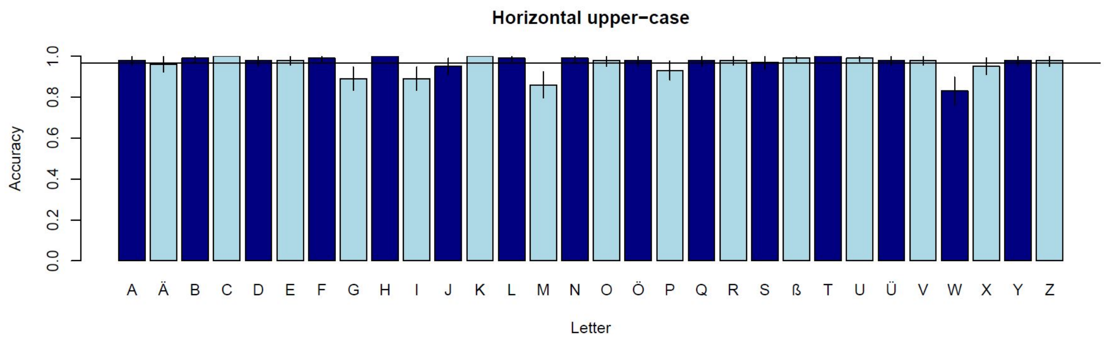
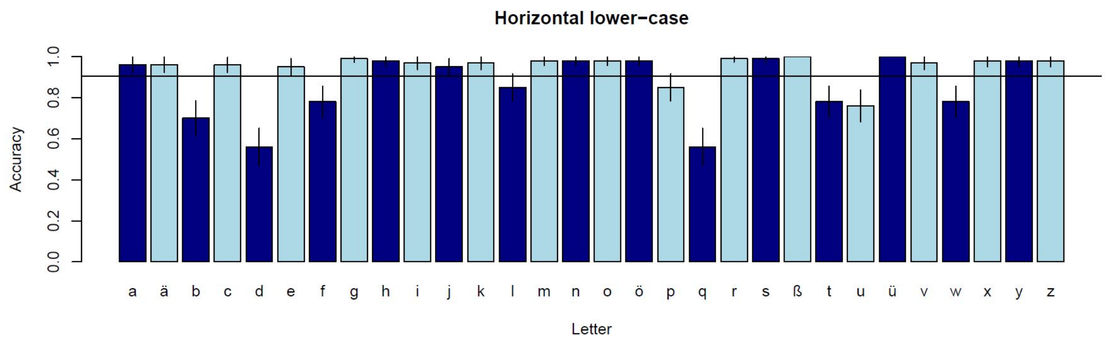


FIGURE 4.5: Experiment 1: Response accuracy for lower-case letters in the horizontal condition



Reaction times Response times are shown in Figure 4.6, 4.7, 4.8, 4.9. Results from the linear mixed-effects model for response times are shown in Table 4.1. Overall response latency was *M* = 859 ms, *SD* = 295 ms. First, there was a main effect of mirror-condition. Post-hoc contrasts revealed that in the Normal mirror-condition letters, *M* = 762 ms, *SE* = 18 ms, were identified Δ = 59 ms faster, *SE* = 0.189, z = -29.05, $p < .001$, than in the vertical mirror-condition, *M* = 821 ms, *SE* = 20 ms. In addition, letters in the horizontal mirror-condition, *M* = 900 ms, *SE* = 22 ms, were identified Δ = 79 ms slower, *SE* = 0.189, z = -52.5, $p < .001$, than in the Vertical mirror-condition.

In addition, there was a main effect of case, indicating that upper-case letters were recognized faster than lower-case letters. Post-hoc contrasts revealed that upper-case letters *M* = 802 ms, *SE* = 19 ms, were identified Δ = 47 ms faster, *SE* = 0.232, z = 51.31, $p < .001$, than lower-case letters, *M* = 849 ms, *SE* = 20 ms. However, the main effect of case was qualified by a strong interaction between mirror-condition and case as shown in Figure 8. Post-hoc contrast revealed that in the horizontal mirror-condition, lower-case letters, *M* = 942 ms, *SE* = 23 ms, were identified Δ = 84 ms slower, *SE* = 0.047, z = 21.13, $p < .001$, than upper case-letters, *M* = 858 ms, *SE* = 21 ms. Similarly, in the vertical mirror-condition, lower-case letters, *M* = 855 ms, *SE* = 21 ms, were identified Δ = 68 ms slower, *SE* = 0.041, z = 18.55, $p < .001$, than upper case-letters, *M* = 787 ms, *SE* = 19 ms.

The main effect of letter and the interaction between letter and case indicated that there were substantial overall differences in response latencies to specific upper- and lower case letters.

In addition, for response latency there was also a strong interaction between mirror-condition and letter, indicating that individual letters were affected differently by vertical and horizontal mirroring.

There were several letters which deviated significantly from the mean of all other letters in the respective condition (Bonferroni adjusted $p = 0.0017$). While for the reaction time measure we can only infer which confusions may have occurred based on inter-letter-similarity of specific letter pairs, the confusion data can provide further information on potential confusions and will thus be taken into account in the interpretation of the results.

In the vertical mirror-condition, the upper-case the letters "Ä" (t = 4.85), "J" (t = 5.78), "Ö" (t = 3.47), "P" (t = 9.58), "ß" (t = 4.44) and "Ü" (t = 5.19) were most severely affected by mirroring (see Figure 4.6). The increased reaction times for the letter "P" are likely the result of mirror-confusions because the mirror-letter "ᑫ" is similar to the lower-case letter "q". This was also confirmed by the confusion data which revealed the highest proportion of confusions between these two letters. By contrast, as the letters "Ä", "Ö", and "Ü" don not change their appearance when mirrored vertically, the increased reaction times for these letters cannot result from mirror-confusions. Inspecting the confusion data revealed that the letter "Ö" was confused with the letter "O" and the letter "Ä" was confused with the letter "A", indicating that these confusions occurred because of visual similarity rather than mirror-confusability. However, the letter "Ä" was also confused with the letter "Ö", which may be a result of the spatial proximity of these letters on the keyboard. In the similarity matrix of Simpson et al. (2013), the letter pairs "Ä" and "A" as well as "Ö" and "O" had similar high ratings (6.67 and 6.57, respectively) whereas the letter pair "Ä" and "Ö" had received rather low similarity ratings (2.43 out of 7), indicating that confusions of "Ä" and "Ö" most likely reflect errors based on spatial proximity on the keyboard. The letter "ß" was not confused at all but this letter does not have a mirror-image counterpart nor is it similar to other letters when mirrored vertically (e.g.,"ɑ"). This suggests that the letter "ß" revealed increased reaction times because it is extremely infrequent. For the letter "J" the case is less clear. While the confusions data revealed that the mirror-letter "Ꞁ" was confused with the letter "I", suggesting visual similarity effects, it is also plausible to believe that "Ꞁ" could have been mirror confused with the lower case letter "t". However, the t-values for the letters "Ä", "J", "Ö" and "ß" are similarly low compared to the t-value of the letter "p", which suggest that the effects of the "J" also merely reflect confusions based on visual similarity rather than mirror-confusability.

In the vertical mirror-condition, the lower-case the letters "ä"(t = 3.96), "b" (t = 14.65), "d" (t = 13.69), "p" (t = 14.42), and "q" (t = 15.91) were most severely affected by mirroring (see Figure 4.7). The increased reaction times for the letters "b", "d", "p" and "p" are likely the result of mirror-confusions because these letters have an exact mirror-image counterpart (e.g. b vs d), which was also supported by the confusion data. By contrast, as the letters "ä", and "a" are unlikely to be mirror-confused, we again examined the confusion data which revealed - as in the case of the upper-case letters - the letter "ä" was confused with the letter "a" and "ö", indicating that confusions occurred either because of visual similarity or because of the spatial proximity of both letters on the keyboard. This assumption is also supported by the rather low t-values for the letter "ä" compared to the t-values of the letters "b", "d", "p" and "p". Similarly, in the matrix of Simpson et al. (2013), the letter pair "ä" and "a" also received very high similarity ratings (6.35 out of 7). By contrast, the ratings in this matrix for the letter pair "ä" and "o" were not as high (4.60 out of 7).

In the horizontal mirror-condition, the upper-case the letters "Ä" (t = 3.27), "M" (t = 9.62), "P" (t = 11.85), "ß" (t = 3.00), "Ü" (t = 3.29) and "W" (t = 15.84) were most severely affected by mirroring (see Figure 4.8). The increased reaction times for the letters "M", "P" and "W" are likely the results of mirror-confusions because the letter "M" and "W" are horizontal mirror-image reversals of each other and the letter "ᑲ" is similar to the lower case letter "b". This was also supported by the confusion data. By contrast, again the letters "Ä", "Ö" and "ß" are unlikely to be mirror-confused. Inspecting the confusion data revealed that the letter "Ä" was confused with the letter "Ö", the letter "Ö" was confused with the letter "O" and the letter "J" was confused with the letter "I", indicating that these confusions occurred because of visual similarity rather than mirror-confusability. Again, this view is supported by the rather low t-values for the letters "Ä", "ß" and "Ü" compared to the t-values of the letters "M", "P" and "W".

In the horizontal mirror-condition, the lower-case the letters "b" (t = 16.26), "d" (t = 18.50), "p" (t = 14.35), "q" (t = 16.77) and "w" (t = 7.07) were most severely affected by mirroring (see Figure 4.9). The increased reaction times for the letters "b", "d", "p" and "q" are likely the result of mirror-confusions because these letters have an exact mirror-image counterpart, which was also supported by the confusion data. Similarly, the lower-case mirror-letter "ʍ" was likely to be mirror-confused with the upper-case letter "M".

FIGURE 4.6: Experiment 1: Reaction Times for upper-case letters in the vertical condition

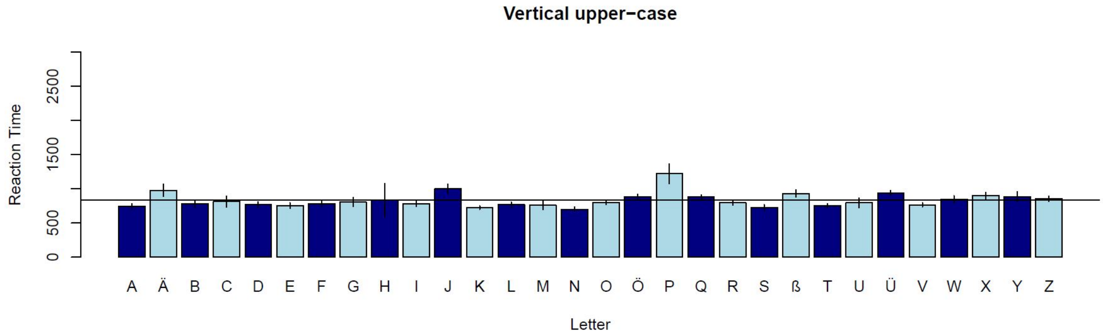


FIGURE 4.7: Experiment 1: Reaction Times for lower-case letters in the vertical condition

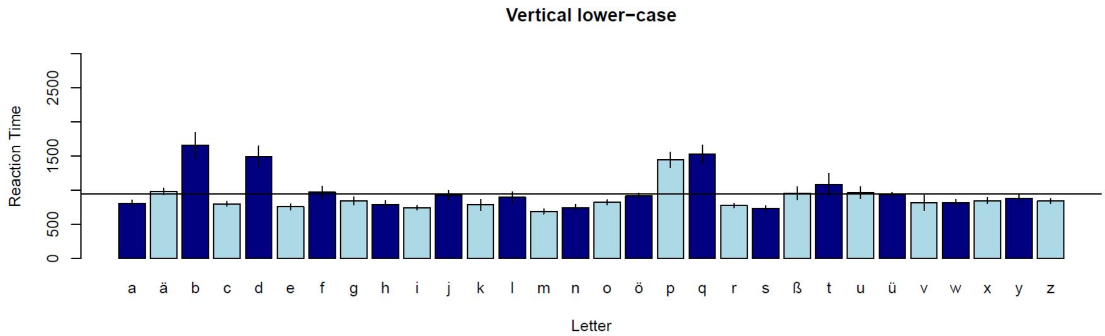


FIGURE 4.8: Experiment 1: Reaction Times for upper-case letters in the horizontal condition

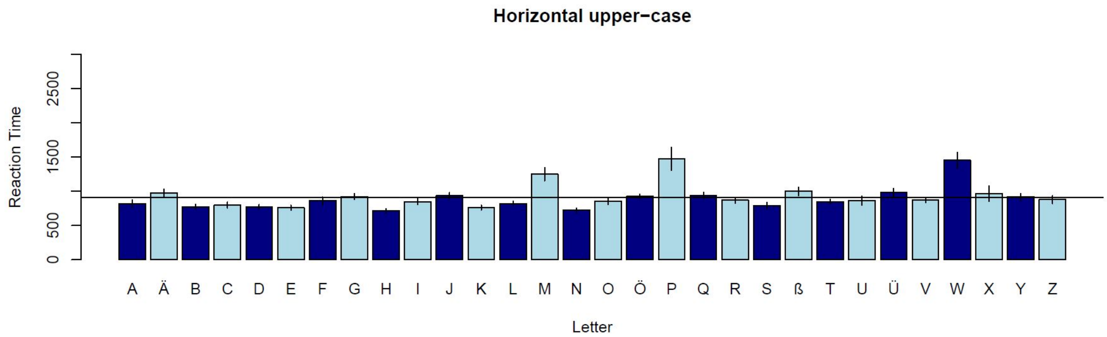
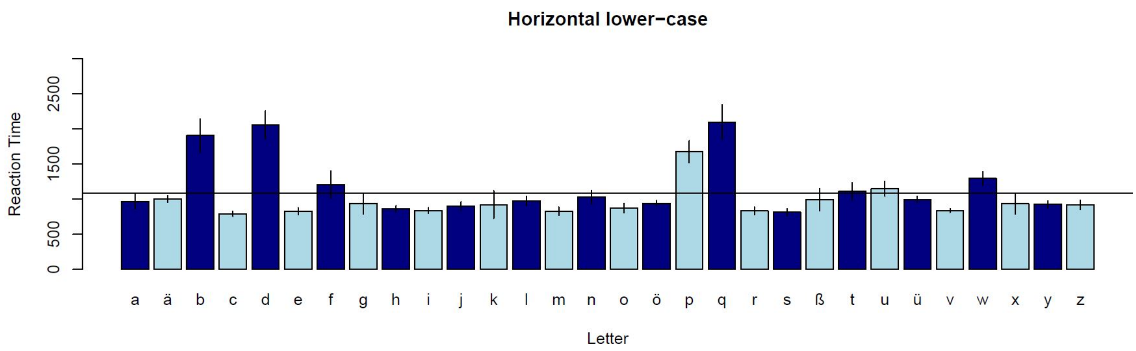


FIGURE 4.9: Experiment 1: Reaction Times for lower-case letters in the horizontal condition



Summary Results Overall, the results show that letters of the Latin alphabet vary substantially in their mirror-confusability and that overall, the upper-case letters are less confusable than the lower-case letters. Furthermore, besides the letters "b", "d", "p" and "q" which do have an exact mirror-image counterpart, there are also letters which are prone to mirror-confusions such as the upper-case letters "P" (in both horizontal and vertical mirroring) as well as the upper-case letters "M" and "W" and the lower case letter "w" (in horizontal mirroring). However, because reaction time by itself is not a metric but a metric is required in order to quantify the mirror-confusability of the Latin alphabet, we computed score.

Confusability-score In order to provide a sensitive measure for a letter's mirror-confusability, both recognition speed and accuracy were combined in a performance score which quantified the recognition difficulty for the normal, the vertical and the horizontal condition separately. The rationale behind combing recognition speed and accuracy is that both measures increase with recognition efficiency. In order to compute the mirror-confusability score, first a performance score for each letter in each condition was computed. In a second step, a mirror-confusability score was computed based on the performance score *difference* between the normal condition and each of the two mirror-conditions.

The performance score ($Comb_i$) for each letter in its upper-case and its lower-case version in each presentation condition (normal, horizontally mirrored, vertically mirrored) was computed based on the ratio of recognition speed Rt_{ji}^{-1} and response accuracy Acc_{ji} which was summed up across participants. We used recognition speed Rt_{ji}^{-1} rather than response latency Rt_{ji} because both recognition speed and accuracy are positive when letters are easily identified.

Thus, for the performance score we computed a combined metric:

$$Comb_i = \sum_{j=1}^{n} \frac{Acc_{ji}}{Rt_{ji}}$$

where j corresponds to the number of letters of the Latin alphabet and n to the number of observations for the letter.

To quantify in mirror-confusability in a vertical (VerConf) and in a horizontal (HorConf) confusability-score, we computed the performance score difference between each mirror-condition and the normal condition (NormComb).

Thus, for the confusability-score we computed the performance score differences:

$$VerConf = NormComb_i - VerComb_i$$

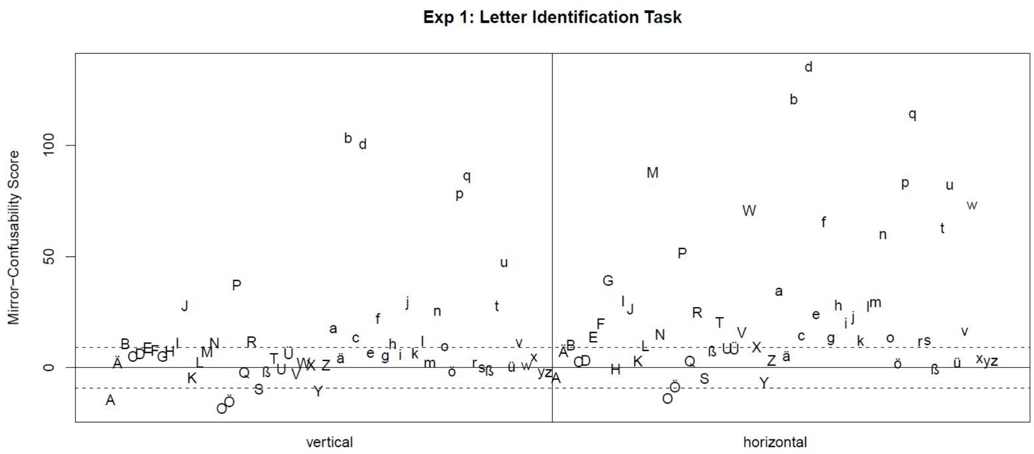
$$HorConf = NormComb_i - HorComb_i$$

Thus, a higher mirror-confusability score for a letter reflects a greater difference between its recognition efficiency in a particular mirror-condition compared to its recognition efficiency in the normal condition. The confusability-scores for both vertical and horizontal mirroring are shown in Table 4.6 (upper-case letters) and Table 4.7 (lower-case letters) and in Figure 4.10.

The overall higher scores in the horizontal mirror-condition as compared to the vertical mirror-condition reveal that horizontal mirroring was overall more disruptive to visual letter identification. To assess the relationship between the horizontal and vertical confusability-scores we computed the Pearson product-moment correlation coefficient for all upper- and lower case letters of the Latin alphabet. There was a positive correlation between the vertical and horizontal confusability-scores for the upper-case, r = 0.54, df = 28, t = 3.396, p = .002 and lower-case letters r = 0.91, t = 11.269, df = 28, $p > .001$ (see Figure 4.11 for upper-case letters and Figure 4.12 for lower-case letters), indicating that both scores measure the same construct.

Turning to the lowers-case letters in the vertical mirror-condition, letters can be divided into letters with a high confusability score and letters with a moderate confusability score. The letters with a high mirror-confusability score of $>= 50$ were the letters "b", "d", "p", "q"

FIGURE 4.10: Experiment 1: Vertical and Horizontal Mirror-confusability Scores for upper- and lower case letters



which were most likely confused with their mirror-image counterpart b/d, d/b, p/q and q/p. Furthermore, there were several other letters which had a moderate confusability score of >= 19 but <= 50: "u", "j", "t", "n", "f" with the corresponding confusions likely being u/n, t/f, n/u and f/t, whereas the letter ť likely reflects a confusions induced by visual similarity with the letter "i" rather than mirror-confusability.

The upper-case letters in the vertical condition were only of moderate confusability and included only two letters: "J" and "P" which were most likely due to the mixed case confusions [/t and ᑫ/q.

For the lower-case letters in the horizontal condition, letters can also be divided into letters with a high confusability score and letters with a moderate confusability score. The letters with the highest confusability score were those with a score of >= 50, including the letters "d", "b", and "q" which were likely to be confused with their horizontal mirror-image counterparts "q", "p", and "d". Furthermore, the letters "p", "u", "w", "f", "t", and "n" had a high mirror-confusability score and were likely to be confused as follows: (p/b, u/n, w/M, f/t, t/f and n/u). There were also letters which fell into the moderate confusability category with a confusability score of >= 19 but <= 50: "a", "h", "m", "l", "e", "j", "i". The mirror-letter version of the letter "a" (e.g. ɐ) was most likely confused with the letter "g" but with its commonly known form "g", rather than with the actual version of the letter used in this experiment. The form "g" is known as the infant form of the letter (Walker & Reynolds, 2003) and is also widely used. Further confusions are likely to be the following: ᴎ/u, ʍ/w, including the mixed-case confusions ɿ/J, and ɓ/G. The rest of the letters with moderate

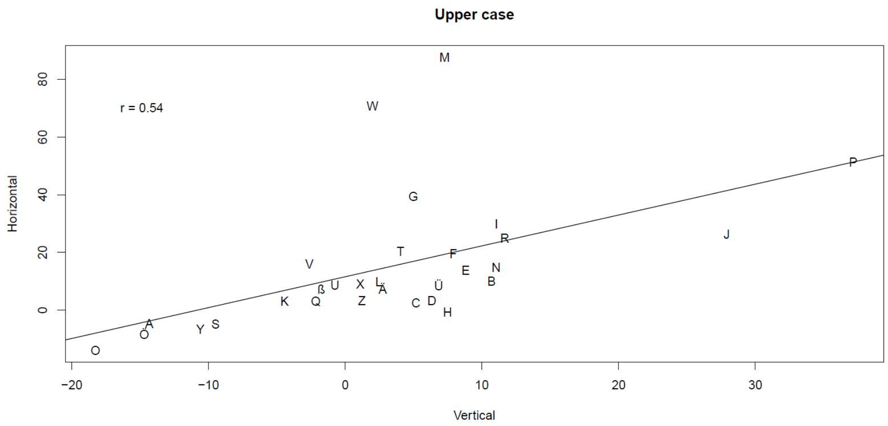


FIGURE 4.11: Experiment 1: Pearson Correlation of Confusability Scores for Upper-case Letters

confusions scores were likely to be confused because of visual similarity rather than mirror-confusability. These include the letter pairs ɿ/i and i/ɿ.

Turning to the upper-case letters in the horizontal condition, there are also letters with a high confusability score and letters with a moderate confusability score. The letters "W", "M", and "p" had a high confusability score of >= 50. The letters "M" and "W" were most likely confused with their mirror image counterpart (W/M and vice versa) whereas the letter "P" was most likely subjected to a mixed case confusion (ь / b). Of moderate confusability with a score of >= 19 and <= 50 were the letters "G", "I", "J", "R", "T", "F" whereby the confusions were likely to be the following: ɘ / e, Я / B, ⊥ / I and Ⅎ / E. The mirror-letter ᒧ was most likely confused with I which is unlikely a mirror-confusion error but rather an error induced by visual similarity. Similarly, as the letter I is symmetrical, its confusion score is likely the result of its visual similarity with the letter l.

4.3.4 Discussion

Our results show that the letters of the Latin alphabet vary considerably in their mirror-confusability. In line with Kolers and Perkins (1969a), we show that vertical mirroring is less disruptive to visual letter identification than horizontal mirroring. Additionally we show that there is a high correspondence between vertical and horizontal mirroring. Similar to Kolers and colleagues, we found that the most confusable letters are those that have an exact or very similar mirror-image counterpart. We extended the work of Kolers and colleagues in that we developed a metric which quantifies the mirror-confusability of the entire Latin

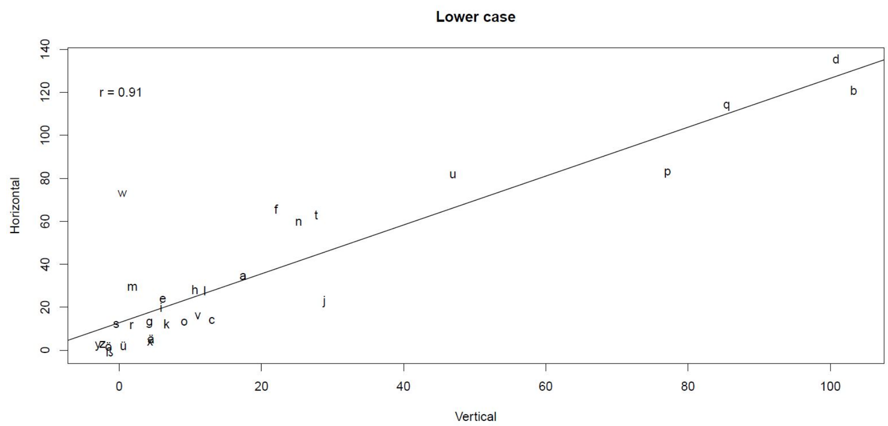


FIGURE 4.12: Experiment 1: Pearson Correlation of Confusability Scores for Lower-case Letters

alphabet (including upper- and lower-case letters) and by taking into account even subtle differences and asymmetries which have previously been reported in the context of confusion matrices (e.g. that in horizontal mirroring "d" vs "b" is more likely to be confused than "b" versus "d"). Furthermore, we show that mirror-confusability is not a characteristic that is confined to reversible lower-case letter pairs (e.g., b vs d) but also affects other letters pairs which increase their inter-letter-similarity when mirrored (e.g., g and g), including mixed-case confusions (e.g., e vs ɘ and G vs G). One limitation this study is that reaction time data can merely reflect mirror-letter interference effects. It cannot, however, "mind read" in that it reveals with *which* competing mental letter representation a specific letter was confused. Nevertheless, the mirror-confusability score which we developed in this study can be used to quantify and manipulate the overall confusability of words which was one of the main goals of Experiment 2.

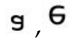
4.4 Experiment 2

4.4.1 Introduction

As Experiment 1 has shown, letters can vary substantially in their mirror-confusability and these confusions are not limited to reversible letters (b, d, p, q) but also include mixed-case confusions (e.g., G vs G). As described in the introduction, previous research has mainly used masked priming experiments in order to examine the impact of reversible letters on visual word recognition in functional reading adults (Soares et al., 2021, 2019; Perea et al., 2011). In these studies, however, only single letters have been manipulated within a word. Furthermore, the only criteria applied for selecting specific letters in these studies was whether they do or they do not have an exact mirror-image counterpart (e.g. b vs d).

Thus, the conclusions which can be drawn from these studies on mirror-interference effects in visual word recognition are limited as they do not consider the entire spectrum of potential confusability effects.

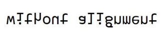
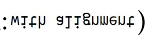
On the other hand, there are studies which have examined the impact of different mirror-transformations on the level of the entire sentence. For example, Kolers (1968) conducted a study in which participants read passages that were approximately 310 words long. When individual letters were mirrored vertically or horizontally and the reading direction was from left-to-right, Kolers found that vertical mirroring was less disruptive to reading than horizontal mirroring. Similarly, in an eye-tracking study conducted by Kowler and Anton (1987), two participants read text with individually mirrored letters, entirely mirrored words or whole texts that were mirrored vertically or horizontally. Results showed that reading text with mirrored letters increased reading times from approximately 60 ms/letter in normal reading to ca. 240 ms/letter when reading text with vertically mirrored letters to approximately 460 ms/letter when reading text with horizontally mirrored letters. In a recent eye-tracking study, Pittrich and Schroeder (2022) examined the cognitive processes involved in reading text with vertically and horizontally mirrored letters. Similar to the effect sizes that have been reported by Kolers, they found that reading text with horizontally mirrored letters took approximately twice as long as reading text with vertically mirrored letters. Their results also revealed that reading text with mirrored letters involved a late checking mechanism that was particularly important for reading text with horizontally mirrored letters.

Unfortunately, none of the afore described studies considered that the variability in word reading times could have been explained by word characteristics such as the proportion of reversible and/or confusable letters within a word. There are good reasons to believe that the propensity of letters to be mirror-confused has an impact on visual word recognition. Even the presence of a single reversible letter within a word has been shown to produce interference effects, although these effects were confined to early, automatic stage of the word recognition process. This suggests that mirror-generalization is merely inhibited in the adult reader but that it keeps affecting word recognition. It is thus plausible to believe that words which comprise several reversible letters (e.g. Abend) may be recognized less efficiently than words which do not comprise reversible letters (e.g. Ehre). Until the present, however, this question has not been addressed empirically. One reason for this is that it is difficult to quantify the overall propensity of a word to be affected by implicit mirror-image reversals. First, because some words may comprise several reversible letters (e.g. Abend) whereas other words just comprise one reversible letter (e.g. Erde). Second, because there are also symmetrical letters which are unaffected by implicit vertical (e.g. A, T) or horizontal (e.g. E, C) mirror-image reversals and some are even resistant to both (e.g. O, H). Third, some letters may be reversible only when mirrored horizontally (e.g. u vs n) whereas they are not affected by vertical mirroring. Fourth, some letters may not have an exact mirror-image counterpart but still be prone to confusions when mirrored (e.g. ). Thus, the overall propensity of a word to be mirror-confused is likely to vary with several factors that altogether make up a word's *mirror-confusability*. The impact of a reversible letter within a word may be attenuated by the presence of symmetrical letters and a word's overall degree of confusability depends on whether letters are reversible, confusable or unchanged when mirrored.

In order to examine whether the variability in reading speed during mirror-reading can be explained by a word's overall mirror-confusability, we conducted Experiment 2. Items were presented in vertically and horizontally mirrored text and participants performed a lexical decision task. We categorized words as either high- or low confusability words and we expected to see that the confusability effects which we had observed in Experiment 1 would permeate to the word level. Thus, we expected that words with a high mirror-confusability would be recognized slower and less accurately than words with a low mirror-confusability.

4.4.2 Methods

Participants We recruited adult participants via the Recruiting System of the University of Göttingen for an online-experiment in which 37 adults participated. The data of three participants were excluded from the analysis: One because the person indicated comprehension problems with the instructions, and a second participant because the person indicated to not have normal or corrected to normal vision. The third participant was excluded because of incomplete data. The remaining 34 participants (age:M = 22, SD = 6, years; 26 female) were all German speakers, and had normal or corrected to normal vision. The study was approved by the Ethics Committee of the University of Göttingen. At the beginning of the study, participants provided informed consent electronically. Participants received course credit for participation.

Word-targets We selected one hundred nouns from the Digital Dictionary of the German language (DWDS) (Geyken, 2007). All words had a normalized lemma frequency > 50. Target words were presented in the same customized mirror-fonts that we had created for Experiment 1. However, for the horizontal font, bitmaps of individual letters were adjusted to a new baseline. This way we avoided changing the common spatial relationships between adjacent letters (i.e. not aligned:  vs aligned: ).

To select the stimuli for the second study, we used the mirror-confusability metric which we had created in Experiment 1. Based on the confusability-scores that we had computed for each upper- and lower-case letter, we categorized words in either high- (e.g. ɓdǝnb - ABEND, ǝpɓuq - ABEND) or low confusability words (e.g. ʇoʅɡǝ - FOLGE, ʇoʅɓǝ - FOLGE) by averaging the confusion score of the individual component letters.

The overall higher scores in horizontal mirroring as compared to vertical mirroring show that horizontal mirroring was overall more disruptive to visual letter identification. To assess the relationship between horizontal and vertical confusability-scores we computed the Pearson product-moment correlation coefficient for all upper- and lower case letters of the Latin alphabet. There was a positive correlation between the vertical and horizontal confusability-scores for the upper-case, $r = 0.61$, df = 28, $p > .001$ and lower-case letters $r = 0.89$, $df = 28$, $p > .001$, indicating that both scores measure the same construct. Thus, words were categorized as high or low confusable based on their horizontal confusability-score.

Words in the high confusable condition had a horizontal confusability-score of > 37 whereas low confusability words of $<= 37$. For example, the word "Lied" would have a horizontal mirror-confusability score of 47.17 because $< L >$ (9.80), $< i >$ (19.94), $< e >$ (23.57) and $< d >$ (135.36) sum up to 188.67 and given that the word has 4 letters, the mean horizontal confusability score of "Lied" is 188.67/4 which corresponds to 47.17. Additionally, we created 100 non-words by substituting one or two letters of existing words that did not form part of the stimuli inventory. All words and non-words used in the experiment comprised 4 to 7 letters.

We conducted a two-sample t-test to compare Levenshtein Distance, word length, bigram frequency and lemma frequency between high- and low confusability words. High confusability words did not differ significantly from low-confusability words regarding their Levenshtein Distance ($t = 1.362$, $df = 86$, $p = .176$), length ($t = 0.222$, $df = 97$, $p = 0.824$), bigram frequency ($t = 0.472$, $df = 96$, $p = .637$), and lemma frequency ($t = 0.369$, $df = 97$, $p = .712$). Descriptives for target words are shown in Table 4.2.

Procedure Adult participants took part in an online-study in which they performed a lexical-decision task. The task was to decide as fast and accurate as possible whether the items presented on the screen were words or non-words. We used 2 (mirror-condition: Vertical vs. Horizontal, within) by 2 (confusability: High vs. Low, within) experimental design. In each block, participants responded to 50 words and 50 non-words. The presentation was

TABLE 4.2: Experiment 2: Descriptives for targets in the high and low confusability condition

	High	Low
Bigram frequency	896689.720	863927.300
	(477421.656)	(408241.085)
Levenshtein Distance	1.090	1.053
	(0.159)	(0.108)
Length	4.940	4.900
	(0.935)	(0.863)
Norm. Lemma Frequency	169.994	161.609
	(149.673)	(175.008)

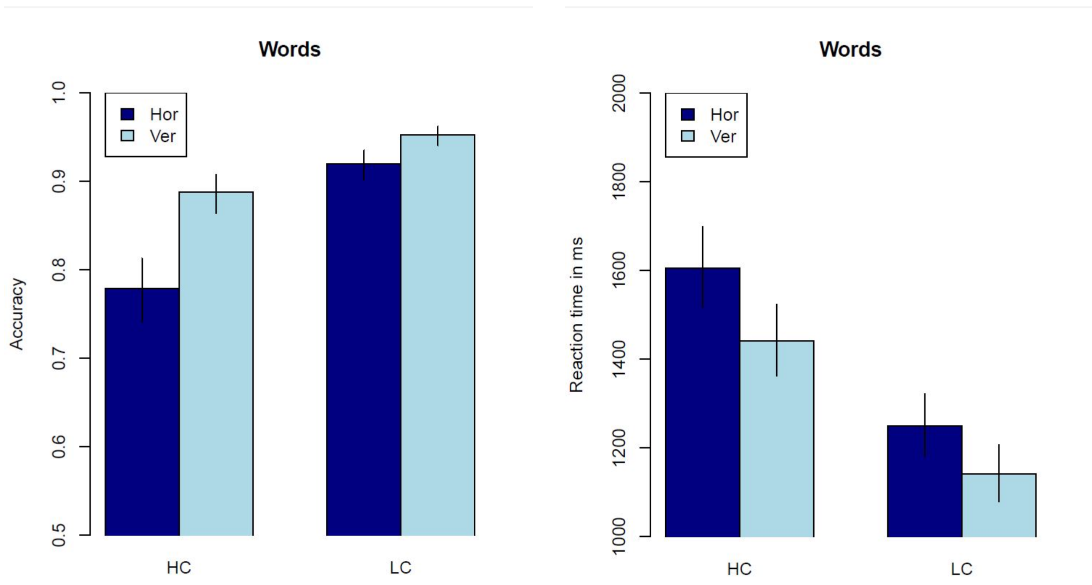
counterbalanced between the vertical and the horizontal mirror-condition whereas high- and low- confusability as well as words and non-words were intermixed randomly. In order to respond, a key press of the letter K for words and the letter D for non-words was required. Reaction times and answers were recorded.

4.4.3 Results

Results were analysed using Linear Mixed Effects models using the lme4 package (Bates et al., 2015) for R (R Core Team, 2013). For response accuracy, a generalized linear mixed-effects model with a binomial link function was used. Log transformed response latencies were analysed using a Linear Mixed Effects model. The data was cleaned in two stages. First, outliers were deleted by excluding all trails that were extremely fast (<=400ms) or slow (>=8000ms). In this step, 0.1% of the trials were excluded. In the second step, we performed a model based outlier deletion with correction adjustment for subject- and item intercepts. In this step, 1.5% of the trials were excluded. In each model we entered mirror-condition and confusability as effect-coded fixed effects. As random effects, random intercepts for participants and items were specified. Overall effects were evaluated using Wald tests and the Anova function of the car package using type III model comparisons. If necessary, post-hoc comparisons were computed using cell means coding and customized contrasts using the multcomp package (Hothorn et al., 2008).

Response accuracy Response accuracies for high-confusability (HC) and low-confusability (LC) words are shown in Figure 4.13 (a). Results from the linear mixed-effects model for response accuracy are shown in Table 4.3.

The strong main effect of mirror-condition indicates that task accuracy varied with presentation condition. Words in the horizontal mirror-condition, M = 86.44 % accuracy, SE =



(a) Accuracy

(b) Reaction Times

FIGURE 4.13: Plots a-b: Experiment 2: Reaction times and accuracy for for high-confusability (HC) and low-confusability (LC) words in the lexical decision task.

54.44 % accuracy, were recognized Δ = 6.21 % less accurately, *SE* = 0.054, z = 6.263, $p < .001$, than words in the vertical mirror-condition *M* = 92.65 % accuracy, *SE* = 54.63 %.

More importantly, there was a strong main effect of mirror-confusability on response accuracy, indicating that responses varied substantially with word-confusability. High-confusability words *M* = 84.09 % accuracy, *SE* = 55.04 % accuracy were recognized Δ = 9.74% less accurately, *SE* = 0.230, z = -4.586, $p < .001$, than low-confusability words *M* = 93.83%, *SE* = 55.33%. The interaction between mirror-confusability and mirror-condition was not significant.

Reaction times Reaction times for High-confusability (HC) and Low-confusability (LC) words are shown in Figure 4.13 (b). Results from the Linear Mixed-Effect Model for response latencies are shown in Table 4.3.

We found a main effect of mirror-condition of mirror-condition. Words in the horizontal mirror-condition, *M* = 1521 ms, *SE* = 76 ms, were identified Δ = 326 ms slower, *SE* = 0.007, z = 17.17, $p < .001$, than words in the vertical mirror-condition *M* = 1195 ms, *SE* = 60 ms.

More importantly, we found a main effect of mirror-confusability. High-confusability words *M* = 1417 ms, *SE* = 76 ms were read Δ = 134 ms slower, *SE* = 0.021, z = -2.361, p = .018, than Low-confusability words *M* = 1283, *SE* = 69 ms. The interaction between mirror-confusability and mirror-condition was not significant.

TABLE 4.3: Experiment 2: Results from the Linear Mixed-Effect Model for Response Accuracies und Latencies

	Accuracy		*RTs*	
Effect (df)	χ^2	p	χ^2	p
Confusability (1)	21.11	$< .001$****	5.58	$< .05$*
Mirror-condition (1)	39.22	$< .001$***	294.91	$< .001$***
Confusability x Mirror-condition (1)	1.34	.09	0.36	0.55

4.4.4 Discussion

In Experiment 2 adults performed a lexical decision task with mirrored words. Our results show that one the word level, mirroring letters vertically is substantially less disruptive to visual word recognition than mirroring letters horizontally. More importantly, we show that the mirror-confusability effects on the letter level permeate to the word level. Words with a high mirror-confusability are identified slower and less accurately than words with a low mirror-confusability. Our results indicate that a word's mirror-confusability is a visual variable which moderates visual word recognition in adults. Until the present, however, no model of visual word recognition can account for the observed mirror-confusability effects, mainly because they lack a visual-orthographic front-end at present (but see Reichle (2021), for a more recent model that might be able to address this issue). However, it has to be noted that although the lexical decision task widely used to study lexical processes, it does not entirely reflect everyday reading experience where words are usually embedded in a linguistic context. In order to gain an insight on whether the observed mirror-confusability vary with task demand, we embedded the target words from Experiment 2 in carrier sentences and asked participants to read them silently while tracking their eye-movements.

4.5 Experiment 3

4.5.1 Introduction

In Experiment 2 we could show that a word's mirror-confusability moderates word recognition times in a lexical decision task. In a lexical decision task, the time needed to reach a decision is the main dependent variable of interest. However, as Kuperman et al. (2013) noted, the lexical decision task incorporates a decision-making component which may not entirely reflect the cognitive processes underlying reading-for-comprehension. One advantage of using eye-movements rather than recognition times as a dependent variable is that eye-movements can be obtained while participants are actually reading. Eye-movements have been shown to reflect the cognitive processes in reading and in particular gaze duration - which is the total fixation time on a target word prior to moving to another word - reflects lexical- and integration processes (**?**).

There are good reasons to believe that confusability effects may differ depending on whether a lexical decisions task or a sentence reading task is performed. One reason for this assumption is that factors such as decision processes (in lexical decision), and text integration processes (in gaze duration) might modulate the "true" effects when comparing results from both tasks (Schilling, Rayner, & Chumbley , 1998). For example, Kuperman et al. (2013) explored the correlations in four different datasets where words were presented in isolation, in isolated sentences, or in sentences embedded in larger contexts. He found low but significant correlations between lexical decision latencies and eye-movements (particularly gaze duration) and that these correlations were largely due to word frequency effects (i.e., the observation that infrequent words are responded to more slowly than frequent words). This suggests that processing times in isolated word processing and continuous text reading are to a certain extent affected by specific task demands and presentation format.

Another reason to believe that in a mirror-reading task, presenting words in context might yield slightly different results than presenting words in isolation is that difficulties in text processing have been shown to increase the use of contextual cues (Nation & Snowling, 1998). Although this effect has been observed in children, it is plausible to believe that adults would apply a similar strategy because in mirror-reading, they are pushed back in their reading skill.

Considering the afore described arguments, we wanted to explore whether confusability effects could still be observed when readers performed a more ecologically valid reading task. To this end, we conducted Experiment 3 in which participants performed a silent reading task while their eye-movements were recorded. Based on the results of Experiment 2 and based on previous research which has found low but significant correlations between lexical decision latencies and eye-movements, we expected that on the word level, fixation related measures (i.e. gaze duration sand total reading time) would be increased in the horizontal compared to the vertical mirror-condition. Furthermore, we expected longer gaze durations and total reading times on high- compared to low confusability words. Our prediction on whether confusability effects vary with task demand are less clear. If in Experiment 3 we find the same pattern of results as in Experiment 2, this would suggest that the "true" confusability effects are not modulated by integration processes. If, by contrast, we obtain a slightly different pattern of results in a sentence reading task, this would suggest that the observed confusability effects are partly modulated by integration processes.

4.5.2 Methods

Participants We recruited 29 participants via the recruitment system of the University Göttingen. The data of two participants had to be excluded from the analysis due to technical problems. The remaining 27 participants (age: M = 22, SD = 3 years, 20 women) were native German speakers, had normal or corrected to normal vision, and no record of reading disability. For the responding of simple comprehension questions about the presented sentences, each individual participant had a performance rate that was $> 80\%$ correct, indicating that sentences were read accurately. The experiment was conducted in the laboratories of the Department of Educational Psychology and was approved by the Ethics Committee of the University of Göttingen.

Apparatus An EyeLink 1000 eye tracker (SR Research, Ontario, Canada) was used to record eye-movements during reading at a rate of 1000 Hz. Stimuli sentences were presented on a 2100 ASUS LCD monitor, with a refresh rate of 120 Hz. Participants sat at a viewing distance of 65 cm with an assisting head and chin rest to reduce head movements. Sentences were presented in the customized Mirror-Consolas font in black, size 18pt, on a white background using the UMass Eye Track 7.10 m software (Stracuzzi & Kinsey, 2006). Participants used a gamepad to indicate the end of each trial and to provide multiple choice responses to comprehension questions.

Materials

Word-Targets Word-targets were the same as in Experiment 2.

Sentences Target words were embedded in carrier sentences which we presented in the same customized mirror-fonts as in Experiment 2. To ensure that the sentence frames were as similar as possible between conditions, they were all 7-12 words long and target words at fifth, sixth or seventh position. For the target words, mirror-confusability and type of mirroring was manipulated and thus, we included 25 nouns in each cell.

Procedure Participants performed a silent reading task while their eye-movements were tracked. We used 2 (mirror-condition: vertical vs. horizontal, within) by 2 (mirror-confusability: high vs. low, within) experimental design. In each block, participants read sentences with 50 high-confusability- and 50 low-frequency words. The presentation was counterbalanced between vertical and horizontal mirror-condition. The task of the participants was to read each sentence silently and answer a short comprehension question by pressing the corresponding key on the keyboard. Questions were presented in normal font.

4.5.3 Results

In a first step, data were cleaned using the popEye package in R (Schroeder, 2019). During pre-processing trials were removed with insufficient calibration quality or too few fixations as well as trials in which a blink occurred directly before or after the target word. In this step, 9.4% of the data were excluded. In addition, we excluded trials with more than 10 runs or 80 fixations. In this step, an additional 1.5% of the data were excluded.

We specified the models for the analyses and conducted the significance test and pos-hoc comparisons in the same way as in Experiment 2.

All duration measures were log-transformed prior to the analysis, but back-transformed in order to ease interpretation. In addition, of the log transformed measures, we excluded all observations deviating more than 2 *SD*s from the person or item mean before the analysis of each measure (excluding 0.1-1.8% of the data).

Local analyses To examine the effects of horizontal and vertical mirroring on the target words which were manipulated according to their mirror-confusability, we computed five dependent measures: first fixation duration, gaze duration, go-past time, and total reading time. Descriptive statistics for all measures are provided in Table 4.4. The results of the corresponding linear mixed effects models are reported in Table 4.4 and depicted in Figure 4.14. Prior to the analysis we excluded all target words with more than 10 fixations or that were reread for more than 4 times (excluding ca. 1.4% of the data). In addition, we removed outlying observations deviating more 2.5 *SD*s from the person or item mean before the analysis of each measure (excluding 0.1 -0.7% of the data).

Skipping probability There was a main effect of mirror-condition on skipping probability. Skipping probability in the horizontal condition, M = 1.9%, SE = 0.44% , was Δ = 6.08% lower than in the vertical condition, M = 7.98%, SE = 1.43%. The main effect of confusability was not significant.

First Fixation Duration There was a main effect of mirror-condition on first fixation duration. In the horizontal condition, first fixation durations, M = 315 ms, SE = 10 ms, were Δ = 70 ms longer than in the vertical condition, M = 280 ms, SE = 9 ms. The main effect of confusability was not significant.

Gaze Duration There was a main effect of mirror-condition on gaze duration. In the horizontal condition, gaze durations, M = 624 ms, SE = 29 ms were Δ = 268 ms longer than in the vertical condition, M = 356 ms, SE = 16 ms. The main effect of confusability was not significant, however, the interaction of mirror-condition and confusability reached significance.

TABLE 4.4: Experiment 3: Model Estimates for First Fixation Duration, Gaze Duration, Go-past Time and Total Reading Time (Milliseconds) to Target Words (SEs in Parentheses)

	Horizontal		*Vertical*	
	HC	*LC*	*HC*	*LC*
Skipping probability	3.627 (17.698)	3.231 (17.698)	12.46 (32.033)	11.587 (32.033)
Total reading time	1182 (674)	966 (674)	589 (414)	532 (414)
Gaze duration	855 (494)	703 (494)	421 (288)	418 (288)
First fixation duration	355 (154)	343 (154)	308 (115)	297 (115)
Single fixation duration	380 (141)	358 (141)	311 (109)	310 (109)

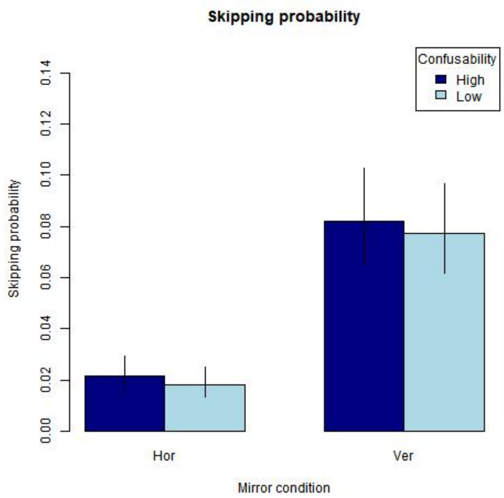
Mean (standard deviation) values for measures on the target word level for High Confusability (HC) and Low Confusability (LC) words. All reading time measures are reported in ms. Probabilities are reported in %.

Post hoc contrasts for the effect of confusability in the horizontal condition revealed that in the horizontal condition, high confusability words, M = 682 ms, SE = 36 ms, were read Δ = 111 ms slower, SE = 0.052, z = 3.372, $p < .001$, than low confusability words, M = 571 ms, SE = 36 ms. In the vertical condition, gaze durations did not differ significantly between high and low confusability words, SE = 0.052, z = 0.136, p = .891.

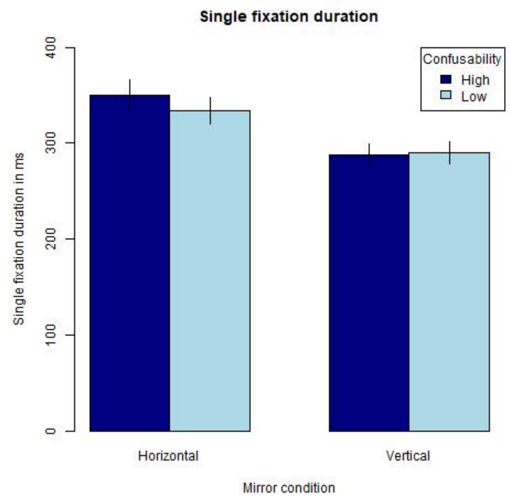
Total reading time There was a main effect of mirror-condition on total reading time. In the horizontal condition, total reading time, M = 876 ms, SE = 46 ms, was Δ = 425 ms longer than in the vertical condition, M = 451 ms, SE = 24 ms. There was also a main effect of confusability and the interaction between mirror-condition and confusability also reached significance. Post hoc contrast for the effect of confusability revealed that high confusability words, M = 671 ms, SE = 39 ms, were read Δ = 82 ms slower than low confusability words, M = 589 ms, SE = 35 ms. Post hoc contrasts for the effect of confusability in the horizontal condition revealed that in the horizontal condition, high confusability words, M = 961 ms, SE = 58 ms, were read Δ = 163 ms slower, SE = 0.062, z = 2.988, p = .002, than low confusability words, M = 798 ms, SE = 48 ms. In the vertical condition, reading times for high and low confusability words did not differ significantly, SE = 0.062, z = 1.206, p = .228.

4.5.4 Discussion

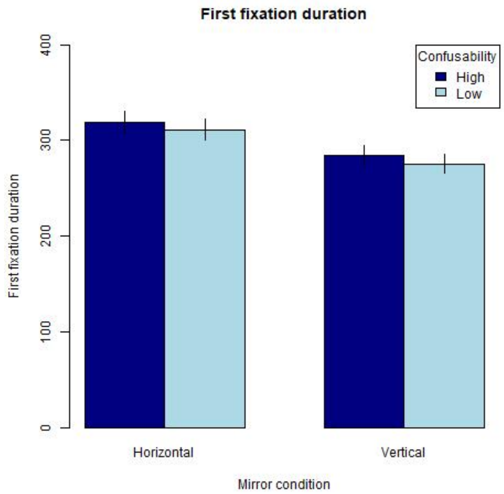
In line with previous research (Pittrich & Schroeder, 2022; Kolers, 1968; Kowler & Anton, 1987) our results show that horizontal mirroring is much more disruptive to reading than vertical mirroring. More importantly, our results show effects of mirror-confusability on word reading times also generalize to a more ecologically valid sentence reading task. However, when words are embedded in context, mirror-confusability moderates word reading



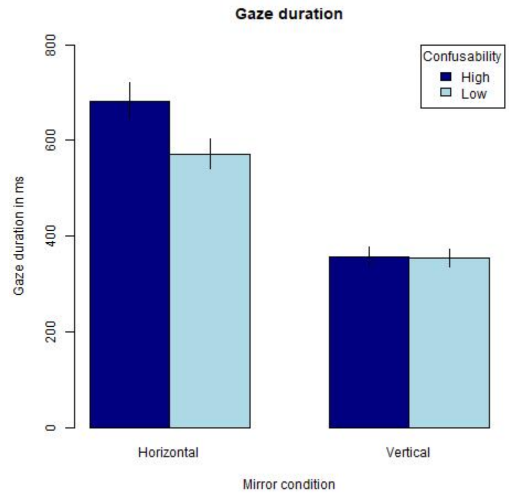
(a) Skipping Probability



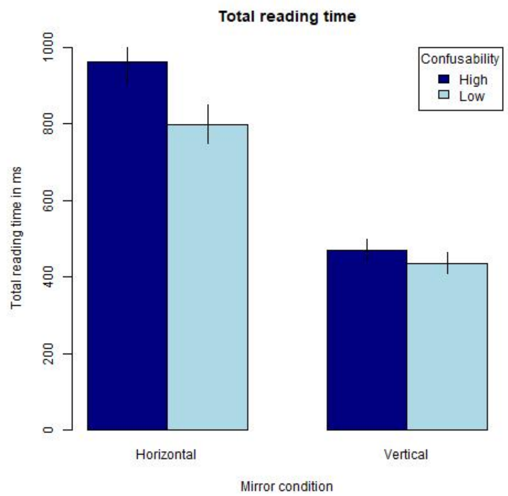
(b) Single Fixation Duration



(c) First Fixation Duration



(d) Gaze Duration



(e) Total Reading Time

FIGURE 4.14: Plots a-f: First Fixation Duration, Gaze Duration, Go-past Time and Total Reading Time.

TABLE 4.5: Experiment 3: Results from linear mixed-effects models for the Five Dependent Measures for High- and Low Confusability Words

	Skipping	*SingleFix.*	*FirstFix.*	*Gaze*	*Total*
Mirror condition	57.00***	55.04***	49.41***	617.84***	902.65***
Confusability	0.17	0.61	1.93	3.78	5.47*
Mirror condition x Confusability	0.08	1.57	0.05	14.04***	6.32*

Note. *p < .05, **p < .01, ***p < .001. Mixed-effects model with Mirror-Confusability and Mirror-Type as fixed effects and Participants and Items as crossed random intercepts.

times only in the horizontal mirror-condition, whereas in the vertical mirror-condition, word reading times do not differ between high- and low confusability words. These findings suggests that the confusability effects in the sentence reading task are modulated by integration processes.

The finding that effects of confusability on word reading times in the horizontal mirror-condition are confined to late eye-movement measures (gaze duration and total reading time) whereas early measures (skipping probability, single fixation duration and first fixation duration) are not affected by word confusability suggests that readers tended to re-fixate words more often in the horizontal condition. Furthermore, the finding that effects of word confusability on eye-movements were only found in the horizontal condition indicates that in this condition, readers tended to employ a late checking mechanism that was particularly pronounced on high confusability words.

By contrast, in the vertical and less difficult reading condition, high- and low confusability words were processed similarly. The absence of confusability effects in the vertical but not the horizontal condition suggests that in the vertical mirror-condition, readers might have been able to compensate for mirror-interference effects more efficiently through the use of contextual cues. By contrast, in the horizontal condition the disruption was too strong and thus, high confusability words required several re-fixations until ambiguity could be resolved.

In sum, in line with previous findings, reading in the horizontal mirror-condition took approximately twice as long as in the vertical mirror-condition. The increased reading times on high confusability words in the horizontal condition were mainly driven by re-fixations, reflecting a late checking mechanism. The result show that a word's mirror-confusability is a visual variable that moderates word reading times and eye-movements in skilled adult readers. However, we did also see that effects of mirror-confusability vary with task demand in that during sentence reading, vertical but not horizontal confusability effects can be compensated. Given that adults reading mirrored text show a similar reading pattern as beginning or less-skilled readers it would be interesting to see whether mirror-confusability also moderates word reading times in children. Future research could address this question. Furthermore, it would be interesting to see whether effects of mirror-confusability on word reading times vary with age and depending on the level of reading skill.

4.6 General Discussion

In the present study, we show that mirror-confusability is a visual property of the Latin alphabet which has a significant reflection in visual letter- and word identification as well as eye-movement control during sentence reading. Additionally, we show that confusability effects vary with task in that when words are embedded in a context, confusability effects can be compensated for vertically but not horizontally mirrored words. Additionally, we provide a score which quantifies the variability and asymmetries in the mirror-confusability of the entire Latin alphabet. The score was validated by showing that confusability effects on the letter level of processing also permeate to the word level of processing. The score can be used by other researcher to quantify and manipulate the mirror-confusability of words in future research which aims to understand how mirror-confusions impact the reading process in different target groups.

We expected mirror-confusability to be a visual factor which moderates letter- and word recognition in adults because mirror-confusions in reading and writing are not related to maturational factors (Lachmann, 2002; Pegado et al., 2014b; Kolinsky et al., 2011). It has been suggested that involuntary mirror-confusions are suppressed or inhibited with reading acquisition. However, when adults are pushed back in their level of reading skill in a mirror-reading task, they process words which comprise confusable letters differently than words which do not comprise confusable letters. This indicates that mirror-confusability is a visual variable which has an impact on word recognition in functional reading adults. The finding that vertical mirroring is consistently less disruptive in letter-, word, and sentence reading suggests that mirror-confusability effects may be diminished because as a result of learning and experience, general visual principles of mirror-generalization favour left-right over up-down generalization (Corballis & Beale, 1976; Rollenhagen & Olson, 2000).

Furthermore, we show that confusability effects are equally strong in horizontal mirroring when words are presented in isolation whereas during sentence reading, confusability moderates eye-movements only in the horizontal mirror-condition. This dissociation between the word- and the sentence level suggest that when confusable words are embedded in a broader linguistic context, readers are able to compensate vertical confusability effects through the use of contextual cues efficiently whereas in the horizontal condition, high confusability words require several refixation in order to resolve ambiguity. The finding that mirror-confusability moderated rather later eye-movement measures (gaze duration and total reading time) suggest that this late checking mechanism was particularly relevant for reading in the horizontal mirror-condition.

In sum, we provide a score which allows to quantify and manipulate the mirror-confusability of letters, words and sentences in both vertical and horizontal mirroring. Our findings can be used to inform the development of models of visual word recognition which, until the present, cannot account for the observed effects of mirror-confusability on visual letter- and word recognition. However, we did not use a paradigm which allows to tap into the early, automatic processes of visual word recognition even though mirror-confusions are likely to occur at an even earlier and automatic processing stage which precedes the processes which we examined here. Thus, future research could examine if and how mirrored letters and mirror-confusability affect the early, automatic processes by using paradigms such as masked priming. Furthermore, it would be interesting to see if the observed confusability effects occur also in children and whether they are moderated by reading expertise.

TABLE 4.6: Mirror-Confusability Scores for all upper-case letters

letter	norm.maj	ver.maj	ver.maj.dif	hor.maj	hor.maj.dif
a	148.55	162.89	-14.33	153.12	-4.57
ä	128.64	125.88	2.76	120.89	7.76
b	168.95	158.24	10.71	158.89	10.06
c	160.07	154.91	5.17	157.46	2.61
d	159.88	153.54	6.34	156.56	3.32
e	175.08	166.27	8.82	161.24	13.84
f	164.63	156.72	7.90	145.00	19.62
g	159.72	154.74	4.97	120.34	39.38
h	172.69	165.21	7.48	173.43	-0.74
i	161.78	150.72	11.06	131.84	29.94
j	153.16	125.25	27.91	126.83	26.34
k	163.37	167.80	-4.44	160.33	3.03
l	161.38	158.92	2.46	151.58	9.80
m	174.90	167.63	7.27	87.20	87.70
n	186.28	175.25	11.03	171.36	14.92
o	130.41	148.68	-18.27	144.31	-13.89
ö	123.87	138.58	-14.70	131.97	-8.10
p	142.99	105.83	37.16	91.58	51.41
q	133.74	135.90	-2.15	130.77	2.97
r	167.03	155.36	11.67	142.14	24.90
s	151.47	160.95	-9.48	156.30	-4.83
ß	133.88	135.64	-1.76	126.57	7.32
t	165.17	161.13	4.04	144.75	20.41
u	157.50	158.25	-0.75	148.94	8.56
ü	134.60	127.76	6.84	125.66	8.94
v	156.29	158.91	-2.62	140.31	15.99
w	139.19	137.20	2.00	68.38	70.81
x	139.44	138.34	1.10	130.31	9.13
y	126.44	137.03	-10.59	133.12	-6.68
z	144.37	143.16	1.21	140.98	3.39

Note. ver = vertical score, hor = horizontal score, min = lower-case, maj = upper-case, diff = difference between mirror-condition and normal condition. The .diff values correspond to the final mirror-confusability score.

TABLE 4.7: Mirror-Confusability Scores for all lower-case letters

letter	norm.min	ver.min	ver.min.dif	hor.min	hor.min.dif
a	167.81	150.41	17.40	133.65	34.16
ä	123.21	118.74	4.47	117.80	5.41
b	167.23	63.93	103.30	46.36	120.87
c	162.77	149.77	13.00	148.87	13.90
d	163.88	63.07	100.81	28.52	135.36
e	169.96	163.84	6.12	146.39	23.57
f	155.10	133.06	22.04	89.29	65.81
g	153.43	149.17	4.26	140.96	12.47
h	169.78	159.15	10.63	141.58	28.20
i	164.30	158.44	5.86	144.36	19.94
j	156.19	127.34	28.85	133.73	22.46
k	162.22	155.57	6.65	149.87	12.35
l	141.78	129.75	12.02	114.18	27.59
m	182.90	181.06	1.84	153.70	29.20
n	184.66	159.42	25.25	125.06	59.61
o	156.24	147.08	9.15	143.25	12.99
ö	131.97	133.46	-1.49	130.12	1.85
p	148.71	71.60	77.11	66.44	82.27
q	142.69	57.25	85.44	29.32	113.37
r	160.99	159.27	1.73	149.57	11.43
s	162.08	162.51	-0.43	150.08	12.00
ß	133.54	134.92	-1.38	134.21	-0.68
t	155.24	127.56	27.69	92.42	62.83
u	164.29	117.35	46.93	82.69	81.59
ü	127.01	126.42	0.59	124.77	2.23
v	158.34	147.28	11.05	142.30	16.04
w	143.79	143.37	0.43	70.92	72.88
x	140.79	136.46	4.34	137.07	3.72
y	135.42	138.43	-3.01	133.52	1.91
z	141.01	143.35	-2.35	138.27	2.73

Note. ver = vertical score, hor = horizontal score, min = lower-case, maj = upper-case, diff = difference between mirror-condition and normal condition. The .diff values correspond to the final mirror-confusability score.

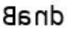
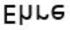
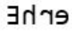
Chapter 5

General Discussion

The present dissertation has investigated the impact of mirror-confusions over the time-course of processing in functional reading adults. Theories on mirror-confusions in reading are unspecified on when and how mirror-confusions affect visual word recognition in functional reading adults. Early, automatic mirror-image reversals have previously been reported only for vertically mirrored letters, although theories on mirror-confusions in reading and visual object recognition make different predictions on whether such confusions should also occur for horizontally mirrored letters. Second, we do not know whether during the early stages of lexical processing, mirror-interference effects operate on early visual letter processing or whether these effects also permeate to lexical stages of the reading process. Third, it remains unknown whether a word's overall *mirror-confusability* is a visual variable that affects the ease with which words can be visually recognized, although there is some agreement that differences in the propensity of letters to be confused when being mirrored can have important consequences for visual word recognition. To address these questions, the present research project has investigated *if*, *how* and *when* mirroring letters affects the reading process across different processing stages, ranging from the early, automatic and unconscious processes up to lexical processes.

Study 1 examined the effects of implicit vertical and horizontal mirror-image reversals of letters during the early, automatic processes of visual word recognition. To this end, Study 1 used an orthographic masked-priming lexical decision task (Exp 1) and an orthographic masked-priming same-different match task (Exp 2), in which the recognition speed for targets preceded by vertical and horizontal mirror-primes was examined. Mirror-primes were the same as the identity prime but they were written in either horizontally (e.g. ɘpɓuq - ABEND) or vertically (e.g. ɒdɘᴎb - ABEND) mirrored letters. Results showed that in lexicality decisions, only vertical mirror-primes produce priming effects, whereas in same-different judgments, both mirror-conditions produce priming effects on target word recognition. Furthermore, in lexicality decisions, only words but not non-words produce mirror-priming effects, whereas in same-different judgments, both words and non-words produce mirror-priming effects. An additional analysis showed that in the same-different match task, priming effects on non-words were moderated by the target's confusability (which was computed based on the proportion of reversible, confusable and symmetrical letters within a prime), whereas in the lexical decision task, priming effects were not moderated by the target's confusability. Together, these results indicate that 1) at an early, automatic processing stage, adults unconsciously mirror-reverse letters as revealed by mirror-priming effects, 2) in line with the Bayesian Reader model, these effects generalize to non-words in a same-different match task, and 3) in the same-different match task, mirror-priming effects occur for primes with both horizontally and vertically mirrored letters. The results can be taken as evidence that early, automatic mirror-image reversals operate both horizontally and vertically and that these reversals are pre- lexical by nature. Furthermore, my results indicate that reversible and confusable letters (mostly the lower-case letters) produce inhibitory effects during this early, pre-lexical stage of visual word recognition as revealed by a reduction in mirror-priming effects for words which comprise confusable letters. This asks for a modification of the parameter for the letter-to-letter inhibition in the current implementation of the Interactive Activation Model (IAM) and the integration of a set of lower-case letters in the model which - in its current implementation - is based on a set of upper-case letters.

Study 2 examined the time-course of interference effects during the reading of mirrored text and was particularly informative on the relationship between the letter-level and the word-level of processing. The eye-movements of adults were analysed as they read half of the sentences of the Potsdam Sentence Corpus in the vertical mirror-condition and the other half in the horizontal mirror-condition. As the Corpus comprises in each sentence a target word that is manipulated for length and frequency, the study disentangled early visual and orthographic processes (visual letter processing) and lexical processes (later language related processing). Results showed that horizontal mirroring produces more disruption in both global and local eye-movement measures than vertical mirroring. In both mirror-conditions, reading relies upon a more serial processing of letters when compared to normal reading as revealed by an in increase in word length effects during mirror-reading compared to normal reading. Furthermore, mirroring letters did not completely break down the reading process because lexical processing was still intact. This was revealed by frequency effects in all reading measures. Most importantly, study 2 revealed interactive effects of mirroring and word-frequency on later eye-movement measures (gaze duration, go-past time and total reading time), indicating that mirroring letters also produces interference effects on the word-level of processing. Frequency effects were larger in both mirror conditions in later reading measures and particularly pronounced in the horizontal condition, indicating that readers apply an additional checking mechanism during lexical verification which is particularly important when reading text with horizontally mirrored letters. The results of study 2 are in line with a cascaded processing architecture in which a word may be matched against items in the mental lexicon even before each individual letter has been recognized.

Study 3 further investigated the impact of mirror-interference effects by examining whether the *mirror-confusability* of words affects the ease with which words can be visually recognized. The mirror-confusability of the Latin Alphabet was quantified in a letter-based score (Exp 1) which was used to manipulate the average mirror-confusability of words in a lexical decision task (Exp 2) and in a sentence reading task (Exp 3). Results show that effects of mirror-confusability permeate from the letter- to the word-level. During single word recognition, words with a high mirror-confusability (HC) (e.g., Horizontal-HC:  ,Vertical-HC: ) are recognized slower and less accurately than words with a low mirror-confusability (LC) (e.g., Horizontal-LC:  , Vertical-LC: ) and this effect is equally pronounced for horizontally and vertically mirrored text. Similarly, during sentence reading, words with a high mirror-confusability receive more and longer fixations than words with a low mirror-confusability. During sentence reading, however, this effect is confined to reading horizontally mirrored text, indicating that vertical confusability-effects are less strong and may be more efficiently compensated through the use of contextual cues when words are embedded in a context. The findings of study 3 thus indicate that mirror-confusability is a visual of property words which has an impact in the ease with which words can be visually recognized.

Taken together, the three studies confirm that in functional reading adults, general visual principles of mirror-generalization are merely suppressed or inhibited and that adults keep mirror-reversing letters. These letter reversals occur at an early, automatic stage of the reading process and thus, they are not consciously perceived by the reader. Furthermore, the studies provide a comprehensive overview on how mirror-effects vary with the time and with the level or unit of processing in that mirroring can produce both priming and interference effects across the different levels of processing. My findings are critical for informing theories on mirror-confusions in reading which make different explanatory attempts on the nature and origin of mirror-confusions in reading. Moreover, the results suggest a cascaded reading architecture and they ask for additional amendments in the current implementation of the IAM.

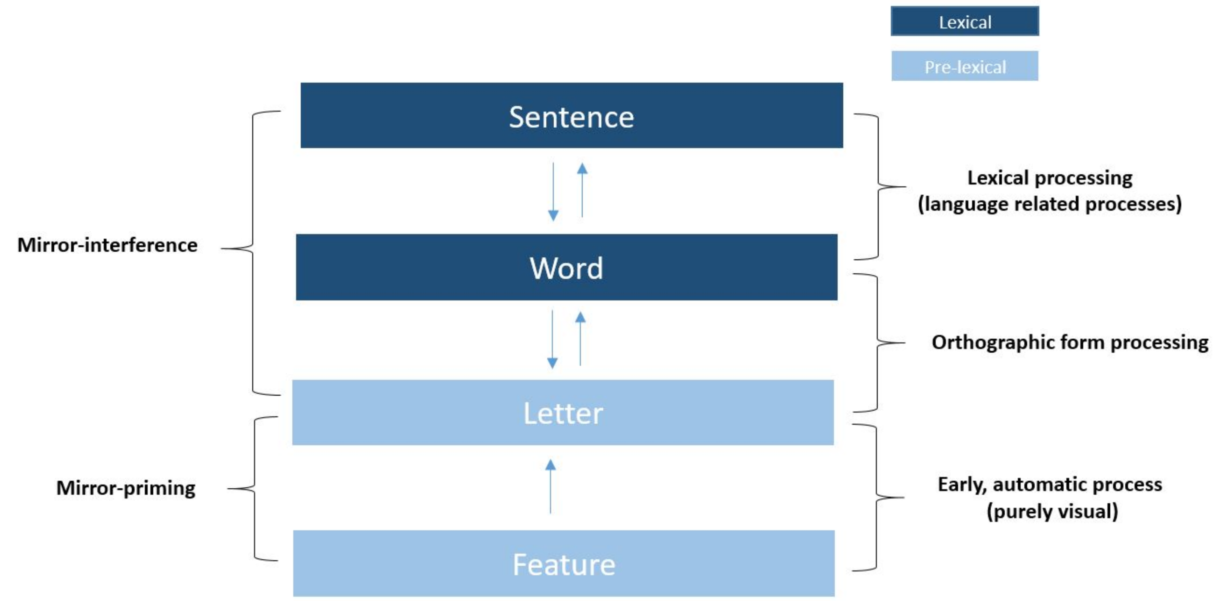


FIGURE 5.1: Schematic representation mirror-effects across time and level/unit of processing

5.1 The Nature and Time-course of Mirror-confusions in Adult Readers

Overall, the results show that mirror-effects in adults vary with the time-course and the level of processing as represented in Figure 5.1 and that they operate within a cascaded processing architecture as represented in Figure 5.2. A cascaded processing architecture assumes not only that processing is cascaded between letter- and the word-level, but also that there is a feedback connection from a word to its constituent letters (Coltheart et al., 2001; Mc-Clelland & Rumelhart, 1981; Rumelhart & McClelland, 1982). By contrast, there is no feedback in these models from the letter or word level to the level of visual features. During a time-window which ranges from the earliest, automatic and purely visual processes up to orthographic form processing, vertically and horizontally mirrored letters are processed like simple allographs by the letter detectors. At this stage, mirror-letters produce priming effects, although these priming-effects are reduced in the presence of confusable letters, indicating the presence of some inhibitory mechanism that is selectively applied to confusable letters. At a later time in the word recognition process, during a time-window which ranges from orthographic form processing up to lexical processing, mirrored letters produce interference effects on word recognition and the overall propensity of a word to be confused moderates word reading times. The exact mechanisms underlying the observed mirror-effects within each of the time-windows are discussed in more detail below.

5.1.1 Mirror-effects during Feature- and Letter Processing

In order to refine theories on mirror-confusions in adult readers, first of all, the time-course and the exact mechanisms of these effects need to be understood. This research project aimed to explore the mechanisms through which mirror-confusions occur at the feature- and letter level processing. The processing of features and letters in visual word recognition involves three stages (see Figure 5.1). First, a pre-lexical stage, which corresponds to a very early, automatic and unconscious stage of processing that occurs within the interface between purely visual and pre-orthographic assembly of features and letters. Second, an early stage of lexical processing, which includes the extraction and identification of the orthographic form of the word (Reingold & Rayner, 2006) and which occurs within the interface between the letter- and word-level of processing. Third, a later stage of lexical processing which corresponds to word recognition itself and which involves language-related processes.

Study 1 (Exp 1 and Exp 2) examined how mirrored letters are processed at a pre-lexical stage of visual word recognition (within the interface between purely visual and pre-orthographic assembly of features and letters). The lexical decision task in Exp 1 was not sensitive enough not capture the entire spectrum of the mirror-priming effect because this task requires lexical activation and thus, it examines later stages of the word recognition process. By contrast, the same-different match task in Exp 2 did not involve lexical activation and thus, the results of Exp 2 are particularly informative about mirror-effects on early, pre-lexical feature- and letter processing, before lexical activation takes place. The matching of targets - and in particular non-words - requires the identification of individual letters within a target with a high degree of certainty. During this identification process, vertical and horizontal mirror-letters pre-activate the corresponding case-dependent letter forms which in turn activate the corresponding, case- independent abstract letter representation as represented in Figure 5.2. This result is particularly relevant for theories on mirror-confusions in reading which assume that - as a consequence of the anatomic symmetry of the nervous system - vertical but not horizontal mirror-letters are processed like the canonical form of the letter. My results indicate that orientation invariance during this early stage of processing occurs both across the horizontal and the vertical mirror axis. These results are in line with the coordinate-system orientation representation (COR) hypothesis (McCloskey, 2009; McCloskey et al., 2006) according to which involuntary mirror-image confusions occur across both object axes when the polarity correspondences between the object axes and the extrinsic axes are confused.

Study 3 (Exp 1) quantified the likelihood of individual letters to be confused when being mirrored vertically and horizontally. Results showed that letters vary substantially in their mirror-confusability. In particular, study 3 (Exp 1) revealed that mirror-confusions do not only impact those letters which have an exact vertical mirror-image counterpart (e.g. b/d). Rather, all letters whose inter-letter similarity increases when being mirrored across an object axis, including the horizontal axis, are likely to produce mirror-confusions (e.g. f/t). For example, as depicted in Figure 5.2, during the visual and pre-orthographic assembly of features and letters, the features composing the mirror-letter "f" can be assembled differently into case dependent letter forms, leading to the pre-activation of two competing abstract letter-representations (i.e. f/F and t/T). The lateral connections that confusable letters establish between each other at the letter level of processing can produce inhibitory effects at an early, automatic stage of processing. This inhibitory link was revealed in study 1 (Exp 2) by a reduction in mirror-priming effects for high confusability targets. At this very early stage of processing, within the interface between purely visual processing and pre-orthographic assembly of the letters, letters are processed like any other visual object and mirror-generalization is not suppressed or inhibited at this processing stage. At a later stage, within the interface between the letter- and the word-level of processing, mirror-generalization is suppressed or inhibited in skilled readers. When adults are pushed back in their reading skill in a mirror-reading task, mirroring letters produces interference effects on word recognition.

5.1.2 Mirror-effects during Orthographic Form and Visual Word Processing

By contrast to pre-lexical processes, the early stages of lexical processing involve the processing of orthographic form which occurs within the interface between the letter- and the word-level of processing.

Study 3 (Exp 2 and Exp 3) and study 2 addressed the question of if and how mirroring letters and a word's overall mirror-confusability affect word recognition during this processing stage. Study 2 revealed that readers are likely to use a late checking mechanism in order to compensate for mirror-interference effects. Study 3 (Exp 2 and 3) revealed that mirroring letters produces interference effects on word reading times and eye-movements and that these interference effects are particularly pronounced for words which comprise a high proportion of confusable letters (high confusability words). The underlying mechanisms of these mirror-interference effects are represented in Figure 5.3.

Until the activation of abstract letter detectors, mirror-letters are processed like simple allographs of a letter because mirror-generalization cannot be suppressed. During a later stage

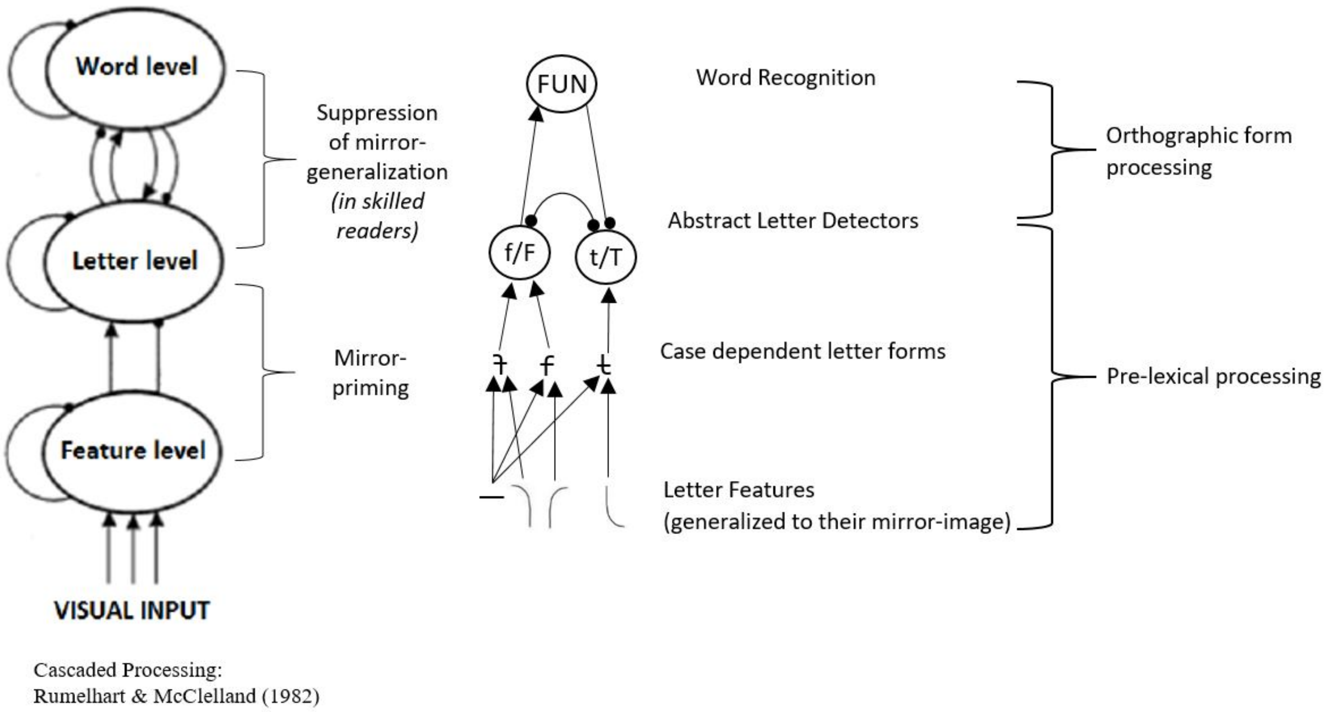


FIGURE 5.2: Schematic representation of mirror-priming effects in a simplified interactive activation model. Priming-effects occur at a pre-lexical stage of processing (i.e. within the interface between purely visual and pre-orthographic assembly of features and the activation of abstract letter detectors). Lines with arrows denote excitatory connections from features to letters and from letters to words. The lines terminated with circles denote inhibitory connections. Confusable letters compete via inhibitory connections at the letter level which leads to a decrease in mirror-priming effects for words which comprise confusable letters during a pre-lexical stage of processing.

Note: Figure left from Rumelhart and McClelland (1982) of processing, between the letter and the word-level of processing, mirror-generalization is suppressed or inhibited in skilled readers (Duñabeitia et al., 2011). A cascaded processing architecture would imply that a word may be matched against entries in the mental lexicon before all letters of the word have been identified (Coltheart et al., 2001). In turn, the letter units receive feedback activation of whole-word orthographic representations.

When adults are presented with mirrored text, the spatial configurations of letters have to be re-learned and - as in less skilled readers - this increases the reader's susceptibility to produce mirror-confusions. If a word is confusable because it comprises ambiguous letters and/or ambiguous local combinations of letters, the word is more likely to activate competing word representations as depicted in Figure 5.3 (left). For example, when the word "Mut" is presented in horizontally mirrored letters, the mirror-letters have a high mirror-confusability and are thus likely to activate competing word representations, in particular, because the letter "M" is highly ambiguous in this context. This ambiguity occurs because both "WUT" and "MUT" have a representation in the mental lexicon. By contrast, when the same word is written in vertically mirrored letters which - in this case - have a low mirror-confusability as depicted in Figure 5.3 (right), the input is less likely to activate competing word representations.

In the IAM, the word node receives connections from the letter units and vice-versa. The connections between the word and the letter-level can either be inhibiting or activating in both directions. In the horizontal condition, the words "MUT" and "WUT" would compete for activation and the letter units "F" and "N" receive inhibitory connections from the word level because neither "MUF", "MNF" or "WUF" are represented as words in the mental lexicon. By contrast, the letter units "W", "M", "U" and "T" receive feedback activation from the word level because they form part of the existing words "MUT" and "WUT". Uncertainty about the letter "M" cannot efficiently be resolved and thus, an additional checking mechanism to verify the correct lexical interpretation later in the reading process is required.

A potential mechanism to verify the correct lexical interpretation later in the reading process could be the use of contextual cues from the sentence level. Study 3 (Exp 2) showed that when the words' mirror-confusability is manipulated and when words are presented in isolation (in a lexical decision task), the word's mirror-confusability is a visual property which moderates words reading times in both mirror-conditions. By contrast, study 3 (Exp 3) showed that when the same words are presented in context, the mirror-confusability of words moderates late word reading measures only in the horizontal but not in the vertical mirror-condition. This indicates when words are presented in context, readers are likely to use contextual cues in order to compensate for mirror-confusability effects. As vertical mirroring is overall less disruptive, this compensation mechanism is more efficient in the

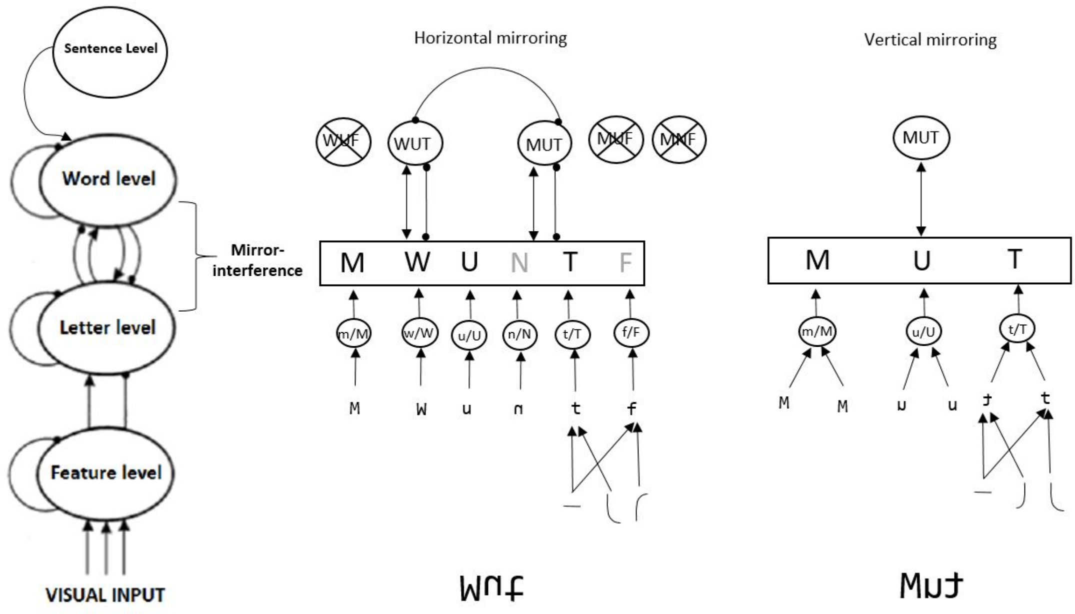


FIGURE 5.3: Schematic representation of mirror-confusability effects in a simplified interactive activation model. Lines with arrows denote that in the depicted example, connections are excitatory, whereas lines terminated with circles denote inhibitory connections. Left: Competing words are activated in the presence of confusable letters. Right: Less confusable letters are less likely to activate competing word representations. Word-to-letter connections activate (black) or inhibit (light grey) letter units. Information from the sentence level may be used to compensate for mirror-confusability effects on the word level

Note: Figure left adapted from Rumelhart and McClelland (1982)

vertical condition, leading to the observation that mirror-confusability effects disappear in the vertical mirror-condition when words are embedded in sentences.

5.1.3 Implications for Theories on Mirror-confusions and Reading

One of the goals of the current dissertation was to inform theories on mirror-confusions in reading which are unspecified on when and how mirror-confusions affect visual word recognition in functional reading adults. In particular, whether implicit mirror-image confusions are confined to vertical confusions or whether they also generalize to horizontal confusions. Furthermore, the exact locus and nature of implicit mirror-image reversals during reading in adults has not yet been identified. The results reported throughout this dissertation challenge theories on mirror-image confusions which suggest that involuntary reversal errors during reading are mainly vertical as suggested by Dehaene et al. (2005), Bornstein (1982), Corballis and Beale (1976), and Gibson et al. (1962), and that they are unlearned as suggested by Dehaene et al. (2005, 2010). Involuntary mirror-image reversals during word recognition in adults were observed in study 1 and they occurred both vertically and horizontally. The evidence from this research project thus implies that implicit mirror-image reversals are not completely unlearned with reading acquisition but rather, that they are suppressed or inhibited. Furthermore, the results imply that these confusions occur at a very early, pre-lexical stage of processing, within the interface of purely visual processing and pre-orthographic assembly of the letters as suggested by Duñabeitia et al. (2011). Kinoshita and Norris (2012) argue that orthographic priming effects are boosted in a same-different match task because this task is particularly suitable for examining the pre-lexical processes in visual word recognition. The absence of horizontal mirror-priming effects in Exp 1 of study 1 - which used a lexical decision task - can thus be explained by differences in the nature of the task. A lexical decision task taps into later stages of the word recognition process because it requires lexical activation. Furthermore, study 1 provided evidence for an inhibitory effect of mirror letters during an early, automatic processing stage, which was revealed by decreased mirror-priming effects on high- compared to low confusability non-words in Exp 2. At a very early, pre-lexical stage of processing, within the interface of purely visual processing and pre-orthographic assembly of the letters, mirrored letters are processed as simple allographs by the letter detectors (Duñabeitia et al., 2011) and this applies to both vertically and horizontally mirrored letters. These findings are in line with theories suggesting that mirror-confusions occur across the object's vertical or horizontal mirror axis (McCloskey et al., 2006; McCloskey, 2009).

5.1.4 Implications for Models of Visual Word Recognition

How exactly letter features are mapped onto abstract representations cannot fully be explained by the current implementation of the IAM. The reason for this is that in its current implementation, the letter feature analysis is based on an uppercase font letter created by Rumelhart and Siple (1974). Hence, the features in the model are selected to construct the letters in the uppercase font. This asks for additional amendments of the model in order to account for the observed reduction in mirror-priming effects for high- compared to low confusability words. Study 3 (Exp 1) revealed that mainly the lower-case letters of the Latin alphabet are prone to be mirror-confused as reflected in a higher mirror-confusability score for lower-case letters. But mirror-confusions are not confined to lower case reversible letters (i.e. b activates b but also d). Rather, mirror-confusions also affect those lower case letters which increase inter-letter-similarity when being mirrored (i.e. t activates t but also f), including cross-case confusions (i.e. ɘ may activate e and/or G). Hence, a set of upper-and lower case letters as well as their corresponding set of features would need to be integrated in the implementation of the IAM in order to account for the observed confusability effects during the early stage of word recognition. Furthermore, the results of study 3 (Exp 1) have shown that confusions can also occur across different fonts. For example, the mirror-letter " ɘ " had a relatively high confusability score because it was likely confused with a commonly known form of the letter "g" which - although not used in the experiment - is widely used. Clearly, one would need to establish a highly flexible letter feature analysis that is based on the upper- and lower case letters of the most widely used fonts. Defining the characteristics of this letter feature analysis system is an enterprise that would be beyond the scope of the present research project. As inhibitory effects of mirror-letters during pre-lexical processing occur because of a simultaneous activation of two competing, abstract letter-representations, the IAM model could be adapted by modifying the parameter which defines the letter-to-letter inhibition, as suggested by Perea, for reversible letters (Perea et al., 2011). However, study 3 (Exp 1) showed that the adaptation of this parameter needs to be much more refined as it needs to take into account that 1) also non-reversible but confusable letters produce inhibitory effects, 2) that letter confusions are asymmetric, and 3) that the level of confusability between letter pairs can range from moderate to high.

5.2 Limitations and Future Prospects

The research conducted and discussed here advances our understanding of when and how mirroring letters produces priming and interference effects on visual word recognition in functional reading adults. Further research will be required in order to understand *why* mirror-interference effects occur and whether a word's mirror-confusability can also predict word reading times when text is presented normally.

There is some agreement in the literature that differences in the letters' propensity to be mirror-confused can have important consequences for visual word recognition. My findings support the idea that mirror-confusable letters produce some inhibitory effects during an early, pre-lexical stage of processing, when features are ensembled into two competing letter forms which in turn activate two competing abstract letter representations. Further research will be required to understand how exactly letter features are mapped onto abstract letter representations. It is possible that during this process, some visual features may be particularly relevant for discriminating among confusable letters and thus be weighted more heavily than other features.

Furthermore, despite the finding that mirror-confusability moderated word reading times and eye-movements in adults during the reading of mirrored text, further research will be required to examine whether these effects also generalize to reading when letters are presented in their upright position. As involuntary mirror-confusions in reading are a phenomenon that has mainly been associated with children and thus, less skilled reading, it would be interesting to examine whether a word's mirror-confusability can predict word reading times and eye-movement behaviour in children. To this end, it would be useful to track the developmental trajectory of mirror-confusability effects on eye-movements in children of different ages and levels of reading skill.

Furthermore, the present research project has revealed that involuntary mirror-confusions during an early stage of processing are not limited to left-right confusions but rather, that they operate across both mirror axes. My findings thus support the notion that mirror-generalization occurs across both the vertical and the horizontal mirror axis of an object. However, effects which can be observed on a behavioural level do not necessarily reflect the same underlying neuronal mechanism. It would thus be necessary to examine whether the processing vertical and horizontal mirror primes in a masked priming paradigm also evokes the same electrophysiological brain responses on the earliest Event Related Potentials such as the N250 component. This would provide further evidence for the assumption that both types of confusions are indeed rooted in the same general mechanism underlying visual object recognition.

5.3 Final Conclusions

The present research project investigated how and when mirroring affects the reading process in functional reading adults. The goal was to define if, when and how implicit and explicit mirroring of letters affects visual word recognition in adults. This was meant to be done on two levels: First, at an early, automatic and unconscious level at which adult readers are unable to inhibit or suppress involuntary mirror-confusions. Second, at a conscious level at which adults were pushed back in their reading skill in a mirror reading task in order examine how mirror-confusable text is processed. The findings suggest that visual principles of mirror-generalization keep affecting the reading process in adults and that mirror-confusability is a visual variable which produces inhibitory effects of visual word recognition. During an early, unconscious level of processing, these inhibitory effects are reflected by a reduction in mirror-priming effects. During a later, conscious level of processing, mirroring produces interference effects on the recognition of letters which permeate to the word level.

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Declaration of Authorship

Hiermit versichere ich, dass die vorliegende Arbeit meine eigene Forschung präsentiert und ich die Arbeit selbständig und ohne Verwendung anderer als der angegebenen Hilfsmittel erstellt und verfasst haben. Die vorliegende Arbeit hat sich in keinem weiteren Promotionsverfahrens befunden. Kapitel 2-3 dieser Arbeit wurden in internationalen Fachzeitschriften veröffentlicht bzw. eingereicht.

Kapitel 3 befindet sich im Reviewprozess beim *Qurarterly Journal of Experimental Psychology*: Pittrich, K., & Schroder, S. (2022). Priming Effects in Vertical and Horizontal Mirror-word Reading.

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Der angeführte Ko-Autor kann bestätigen, dass ich für die Planung, Durchführung, und Auswertung der Studien sowie das Verfassen der entsprechenden Kapitel allein- oder hauptverantwortlich war.

Signed:

Date:
