

What makes a letter a letter? – New evidence for letter-specific processing strategies

Vom Fachbereich Sozialwissenschaften
der Technischen Universität Kaiserslautern
zur Verleihung des akademischen Grades
Doktor der Philosophie (Dr. phil.)
genehmigte

D i s s e r t a t i o n

vorgelegt von

Andreas Schmitt, M.Ed.
aus St. Wendel

Tag der mündlichen Prüfung:	08.12.2016
Dekanin:	Prof. Dr. Shanley Allen
Vorsitzender:	Prof. Dr. Michael Fröhlich
Gutachter:	1. Prof. Dr. Thomas Lachmann 2. Prof. Dr. Cees van Leeuwen

D 386
(2016)

Short summary

Reading as a cultural skill is acquired over a long period of training. This thesis supports the idea that reading is based on specific strategies that result from modification and coordination of earlier developed object recognition strategies. The reading-specific processing strategies are considered to be more analytic compared to object recognition strategies, which are described as holistic. To enable proper reading skills these strategies have to become automatized. Study 1 (Chapter 4) examined the temporal and visual constraints of letter recognition strategies. In the first experiment two successively presented stimuli (letters or non-letters) had to be classified as same or different. The second stimulus could either be presented in isolation or surrounded by a shape, which was either similar (congruent) or different (incongruent) in its geometrical properties to the stimulus itself. The non-letter pairs were presented twice as often as the letter pairs. The results demonstrated a preference for the holistic strategy also in letters, even if the non-letter set was presented twice as often as the letter set, showing that the analytic strategy does not replace the holistic one completely, but that the usage of both strategies is task-sensitive. In Experiment 2, we compared the Global Precedence Effect (GPE) for letters and non-letters in central viewing, with the global stimulus size close to the functional visual field in whole word reading (6.5° of visual angle) and local stimuli close to the critical size for fluent reading of individual letters (0.5° of visual angle). Under these conditions, the GPE remained robust for non-letters. For letters, however, it disappeared: letters showed no overall response time advantage for the global level and symmetric congruence effects (local-to-global as well as global-to-local interference). These results indicate that reading is based on resident analytic visual processing strategies for letters. In Study 2 (Chapter 5) we replicated the latter result with a large group of participants as part of a study in which pairwise associations of non-letters

and phonological or non-phonological sounds were systematically trained. We investigated whether training would eliminate the GPE also for non-letters. We observed, however, that the differentiation between letters and non-letter shapes persists after training. This result implies that pairwise association learning is not sufficient to overrule the process differentiation in adults. In addition, subtle effects arising in the letter condition (due to enhanced power) enable us to further specify the differentiation in processing between letters and non-letter shapes. The influence of reading ability on the GPE was examined in Study 3 (Chapter 6). Children with normal reading skills and children with poor reading skills were instructed to detect a target in Latin or Hebrew Navon letters. Children with normal reading skills showed a GPE for Latin letters, but not for Hebrew letters. In contrast, the dyslexia group did not show GPE for either kind of stimuli. These results suggest that dyslexic children are not able to apply the same automatized letter processing strategy as children with normal reading skills do. The difference between the analytic letter processing and the holistic non-letter processing was transferred to the context of whole word reading in Study 4 (Chapter 7). When participants were instructed to detect either a letter or a non-letter in a mixed character string, for letters the reaction times and error rates increased linearly from the left to the right terminal position in the string, whereas for non-letters a symmetrical U-shaped function was observed. These results suggest, that the letter-specific processing strategies are triggered automatically also for more word-like material. Thus, this thesis supports and expands prior results of letter-specific processing and gives new evidences for letter-specific processing strategies.

Contents

Short summary	2
List of Abbreviations	7
1. Introduction	8
2. Theoretical background	10
2.1. Neuronal and cognitive bases for reading and writing	10
2.1.1. Neuronal bases for reading and writing	11
2.1.2. Phonological bases for reading and writing	14
2.1.3. Visual perception and processing	17
2.2. Reading acquisition and models of reading	18
2.2.1. Modells of reading acquisition	18
2.2.2. Models of reading aloud	25
2.3. Reading disabilities	32
2.3.1. Diagnostic procedure	32
2.3.2. Theories of dyslexia	33
2.3.3. Developmental dyslexia	37
2.3.4. Acquired dyslexia	37
2.4. Congruency effects in letters and non-letters	39
2.5. The Global Precedence Effect	46
2.5.1. GPE and the law of closure	48
2.5.2. GPE and spatial frequency	48
2.5.3. GPE and target placement	49
2.5.4. GPE and stimulus size	51
2.5.5. GPE, target detectability and attentional bias	52

2.5.6. GPE and the categorical nature of stimuli	54
2.5.7. Letter vs. non-letter distinction in GPE	55
2.6. Serial-position effects in letter and non-letter strings	57
3. Research questions	64
4. Study 1: Congruency effects in letters and non-letter shapes	66
4.1. Aim of the study	66
4.2. Experiment 1: The time course of letter recognition and the role of automatization	67
4.2.1. Method	69
4.2.2. Results	71
4.2.3. Discussion	74
4.3. Experiment 2: The influence of reading-like conditions on Global Precedence Effect in letters and non-letter shapes	76
4.3.1. Method	77
4.3.2. Results	79
4.3.3. Discussion	80
4.4. General Discussion	84
5. Study 2: Training study: Can letter-specific processing be transferred?	86
5.1. Aim of the study	86
5.2. Method	87
5.2.1. Participants	87
5.2.2. Material and Procedure	88
5.3. Results	91
5.4. Discussion	93
6. Study 3: Global Precedence Effect in children with poor reading abilities	97
6.1. Aim of the study	97
6.2. Method	98
6.2.1. Participants	98
6.2.2. Diagnostic procedure	99

6.2.3. Material	99
6.2.4. Procedure	100
6.3. Results	102
6.3.1. Interactions with Group	103
6.3.2. Children with normal reading skills	104
6.3.3. Children with poor reading abilities	104
6.4. Discussion	105
7. Study 4: Serial position effects in mixed letter/non-letter strings	108
7.1. Aim of the study	108
7.2. Method	112
7.2.1. Participants	112
7.2.2. Material	112
7.2.3. Procedure	113
7.2.4. Results	113
7.2.5. Results of RT Analysis	114
7.3. Discussion	120
8. General discussion	123
8.1. Temporal and visual constraints of letter processing	124
8.2. Transferability of letter-specific processing strategies	126
8.3. Letter processing and reading skills	127
8.4. Letter processing in whole word reading	129
9. Summary and Conclusion	132
References	134
Acknowledgement	163
A. Curriculum Vitae	165

List of Abbreviations

2AFC	two-alternative forced choice
ANOVA	analysis of variance
DRC	dual-route cascaded model
EEG	electroencephalography
ER	error rate
FCD	functional coordination deficit
FCM	functional coordination model
fMRI	functional magnetic resonance imaging
GPC	grapheme-phoneme correspondance
GPE	Global Precedence Effect
ISI	inter-stimulus intervall
IQ	intelligence quotient
RAN	rapid automatized naming
RT	reaction time
VWFA	Visual word form area

1. Introduction

Reading as a cultural technique is a relatively young achievement in human history. Hence, it is not determined by evolutionary brain development, but by cognitive processes, based on modifications of earlier developed brain structures.

Writing enables us to memorize and transport information, ideas and even emotions, as long as the addressees possess the necessary skills to decode this written information in an appropriate manner. Thus, it is not surprising, that one of the most progressive steps in the modern history – the "Age of Enlightenment" – was initialized by literalization of a broad majority of the society. However, literacy skills still become more important, regarding today's communication. E-Mails, SMS, Social Media and Messenger Services enter more and more in business as well as private communication. Therefore, it is important to enable all people to acquire the necessary skills to take part in modern communication.

Unfortunately, the ability to read and write is not innate. Reading and writing skills have to be learned during a long process of learning. However, some children seem to fail to appropriately acquire these skills. To develop efficient support for these children, it is necessary to understand the cognitive processes which enable proper letter and word recognition, fluent reading and reading comprehension. Although a lot of work was already done in this field, there are still open questions and conflicting theories about the basic principles of reading and reading acquisition. Is reading based on "neuronal recycling" of earlier developed brain structures, and mediated by increasing familiarity with meaningful units or are there reading specific processing strategies, which are generally different to other object recognition strategies?

The current thesis aims to clarify some of these questions and supports the hypothesis of letter and reading specific processing strategies. To enable a proper usage of these strategies, automatization during reading acquisition seems to play

a crucial role. Hence, this thesis will focus this finding and thereby demonstrate that familiarity and nameability are more modulating factors of letter and word recognition, rather than basic requirements. Since automatization occurs under specific conditions, context effects may have a large influence of the appearance and efficiency of the strategies. Moreover, the degree of automatization may correlate with the degree of reading skills. These relations will be subject of the different studies. Furthermore, this thesis aims to close the gap between single letter processing and whole word reading strategies. Letter processing is often ascribed to sensory processes, whereas for reading whole words, the influence of cognitive processes is more obvious. However, the following studies will show, that also letter processing is based on cognitive processes, as a result of modification of pre-existing skills and automatization during reading acquisition. During reading acquisition, single letter processing strategies are not replaced by the ability to visually recognize whole words. Letter processing strategies are still integrated in word decoding. Both, letter and word recognition, are based on common specific processing strategies.

Reading requires more than a "cultural recycling" of neuronal structures. It requires the development and automatization of specific analytic processing strategies.

2. Theoretical background

2.1. Neuronal and cognitive bases for reading and writing

Reading and writing are not innate abilities, but rather acquired skills, which are developed during several phases of reading acquisition and related to modification and progression of a bunch of cognitive strategies (e.g., Ehri, 1995; Frith, 1986; Marsh, Desberg & Cooper, 1977).

In the timeline of human development and evolution, reading is a relatively young achievement and underwent a process of evolution itself (see Wolf & Wiese, 2009). Starting from the early scriptures of *Sumerian cuneiform scripture*, through various modifications of *syllabary* (e.g., *Linea A* and *Linea B*), it took more than 3000 years to establish the modern alphabetic system which we use today. However, during this phase of human history there was no significant evolutionary improvement of our brain (Chase & Dibble, 1987; Davidson & Noble, 1989; Klein, 1995). In other words, there is no innate brain area which is specialized for reading acquisition. This means that reading ability is based on brain structures that are developed in different phases of human evolution, especially those which are essential for processing of speech and object recognition (Cohen et al., 2000; Friederici & Lachmann, 2002). Thereby, speech itself is a relatively young achievement and brain structures that are responsible for speech processing are younger than those brain structures that are integrated in object recognition (Dehaene & Cohen, 2007; Lachmann, Khera, Srinivasan & van Leeuwen, 2012). There are a lot more factors influencing reading and reading ability, such as general intelligence (IQ), performance of attention, perception and memory, oculomotor and fine motor skills (Steinbrink & Lachmann, 2014; Steinbrink, Schwanda, Klatte

& Lachmann, 2010). However, object recognition and speech perception abilities, especially phonological awareness (Wagner & Torgesen, 1987), seem to be the best predictors for performances of reading abilities (see Snowling & Hulme, 2007; Steinbrink, Groth, Lachmann & Riecker, 2012; Steinbrink & Lachmann, 2014; Steinbrink et al., 2010, for a review). Hence, in addition to the neuronal bases for reading and writing, the current chapter will focus on these cognitive abilities.

2.1.1. Neuronal bases for reading and writing

Reading includes *orthographic processes* (e.g., letter and word detection), *phonological processes* to encode the letters into phonemes, *lexical processes*, which especially are important for whole word reading (see Chapter 2.2.2) and *semantic processes*, which enable fluent reading by acquisition of content in short- and long-term memory. We assume that these processes are integrated in a highly developed cortical network, which is acquired during reading acquisition (Sandak, Mencl, Frost & Pugh, 2004). This network enables parallel processing of orthographical, phonological, lexical and semantic information.

Since auditory as well as visual skills are required, this network should include and connect previously developed areas, which are used for object recognition as well as speech perception and processing (Schlaggar & McCandliss, 2007). Furthermore, during reading acquisition some brain areas become specialized for processing written language. This specialization was shown in functional magnetic resonance imaging (fMRI) and electroencephalography (EEG) studies (e.g., B. A. Shaywitz et al., 2002; Turkeltaub, Gareau, Flowers, Zeffiro & Eden, 2003; see also Schlaggar & McCandliss, 2007, for a review). Learning to read is connected with a shift from right to left in hemispherical activity. In beginning reader, both hemispheres are involved almost equally in the reading process; however, with increasing reading experience the activity in the right hemisphere decreases, whereas the left-hemispherical activity increases (T. T. Brown et al., 2005; Schlaggar et al., 2002; B. A. Shaywitz et al., 2002). The bilateral regions which are activated in beginning readers are thought to be responsible for object recognition. In skilled readers, letters and words are processed almost completely by the specialized left-lateralized region, known as the *visual word form area* (VWFA;

Cohen, 2002; Cohen et al., 2000; McCandliss, Cohen & Dehaene, 2003). Nevertheless, the involvement of the specialized left-lateralized regions differs, depending on the stage of reading experience and specific word features (e.g., complexity and familiarity).

Pugh et al. (2000) differentiate between three circuits (see Figure 2.1): (1) The *anterior circuit*, located in the inferior frontal gyrus, is associated with, sequencing and control of speech-gestural articulatory recoding. It is involved in silent reading and naming. (2) The *dorsal circuit* (temporo-parietal) is associated with analytic processing necessary for learning to integrate orthographic features with phonological and lexical-semantic features of printed words. Both circuits enable beginning readers as well as skilled readers to read unfamiliar words or non-words by decoding the single letters and blending those to an entire word (S. E. Shaywitz & Shaywitz, 2008). Since for beginning readers most words are unfamiliar, these circuits play an important role in their reading process and enable them to increase their orthographical, semantic and lexical knowledge. This, in accordance to B. A. Shaywitz et al. (2002), shows that beginning readers especially benefit from the *dorsal circuit*. With increase in reading experience, (3) the *ventral circuit* (occipito-temporal) becomes more important. The *ventral circuit* constitutes a fast word identification system, which underlies fluent word recognition in skilled readers (see Schlaggar & McCandliss, 2007). This system enables them to recall automatically phonological information of the whole word from their long-term memory (Pugh et al., 2000; Sandak et al., 2004).

Although each circuit is specialized to process specific requests of reading, these circuits should not be understood as completely independent systems, but rather as interacting networks, in which each system affects another and is constituted on each other (see Figure 2.1). In beginning readers, the *dorsal* and *anterior circuits* are necessary to read unfamiliar words. However, with increasing reading experience both circuits are used as mediators to train the *ventral circuit* to recognize frequent orthographic patterns and enable fast processing of familiar and irregular words (Schlaggar & McCandliss, 2007; Steinbrink & Lachmann, 2014).

As explained before, the left-lateralization of brain regions, which are acquired for reading (see Figure 2.1), reflects the observation that the processing of spoken language (e.g., decomposing spoken language in single *phonemes*; see

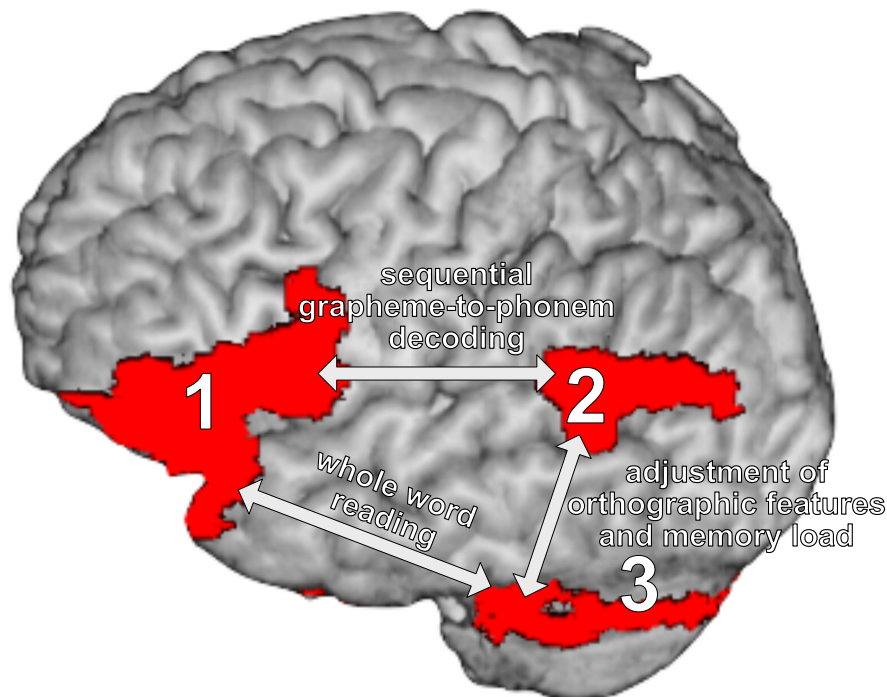


Figure 2.1.: Reading circuits. The *anterior circuit* (1) controls sequencing and phonological output, the *dorsal circuit* (2) integrates orthographic, phonological and lexical-semantic features and the *ventral circuit* (3) enables memory-based word identification (adapted from Pugh et al., 2000).

Chapter 2.1.2) is also connected to processing of written language. The reading related brain regions include some areas, which are essential for producing and understanding language. The *anterior circuit* includes for example the *Broca area*, which is involved in speech production; the *dorsal circuit* includes the *Wernicke area*, which is related to comprehension and understanding of language (Blank, Scott, Murphy, Warburton & Wise, 2002; Pugh et al., 2000).

Since these brain regions for spoken and written language are connected, we assume differences in their neuronal structure and activation patterns, depending on the language and orthography. On the one hand, in German (as well as Italian, Finnish and Greek) the orthography is very *transparent*, i.e., each letter represents one sound of spoken language (strong grapheme-phoneme correspondence; see also Chapter 2.2.2) and each sound in spoken language could mostly be represented by

one letter (or in case of diphthongs two letters). On the other hand, e.g. English and French orthographies are more *intransparent*, i.e. the letters can represent different sounds and sounds can be represented by different letters or letter combinations (e.g., "tough" and "though"; see also Chapter 2.2.2). Therefore, in the more intransparent orthographies larger units (i.e., combinations of letters) are more important to understand written language. Paulesu et al. (2000) demonstrated, that those differences in orthography influence the cortical network. For transparent as well as for intransparent orthographies all reading circuits are used, however, in more transparent orthographies the dorsal circuit is more activated during reading, whereas in intransparent orthographies acquisition of the ventral circuit is more important.

2.1.2. Phonological bases for reading and writing

Phonological information processing

According to Wagner and Torgesen (1987) *phonological information* is used to process spoken and written language. *Phonemes* can be understood as the smallest distinguishable units of spoken language. *Phonological perception* describes the ability to differentiate these units, which could even sound very similar (e.g., the /b/ in "bad" and the /p/ in "pad"). These *phonemes* in spoken language are represented in *graphemes* in written language. This *grapheme-phoneme correspondence* (GPC) explains the importance of phoneme perception for reading acquisition. Beginning readers have to learn these grapheme-phoneme relations (Füssenich & Löffler, 2008) to encode spoken language into written language. Therefore, it is necessary that they are able to distinguish those phonemes. Several studies could demonstrate, that the *phoneme perception ability* is a crucial factor to predict future reading performance in beginning readers (e.g., Clark, Brruininks & Galman, 1978; Kavale, 1982; Kavale & Forness, 2000). However, it is possible that there is an interaction between learning to read (i.e., learning *grapheme-phoneme correspondence rules*) and the ability to discriminate between different phonemes (McBride-Chang, 1996).

Closely related to this *phoneme perception*, Wagner and Torgesen (1987) divided the *phonological information process* into three sub categories: a) *phono-*

logical awareness, b) *phonological recoding in lexical access* and c) *phonetic recoding in working memory*, explained more detailed in the following paragraphs.

Phonological awareness

Phonological awareness describes the awareness of the sound structure of language, meaning the ability to ignore lexical and semantic contents of words and decompose these words into their smallest distinguishable units. The phonological awareness is reflected by the fact that phonemes could be detected and manipulated in words. This ability normally begins in early childhood and can be observed, for example, when children consciously start to manipulate single sounds to build rhymes (e.g., "dad", "bad", "fat" ...). The phonological awareness also includes the awareness of larger structures of speech, for instance, *syllables*, which again are bindings of vocals and consonants. However, it is difficult to determine exactly the beginning and ending of syllables (Balmuth, 1982).

It is obvious that this ability to detect phonemes and synthesize those into syllables and words is fundamental for reading and writing ability. To read a written word, as for example "Mama", children must be able to decode the included graphemes <m> and <a> into the phonemes /m/ and /a/ to blend them to syllables (e.g., <ma>) and words "Ma-ma" (see Steinbrink, 2006). To transform spoken into written words, the *phonological awareness* is necessary to use a reversed procedure, meaning to decompose the words into syllables and phonemes and decode those into graphemes. Although phonological awareness starts to be developed in children just before school entry, there seems to be an interaction with increasing letter knowledge during reading acquisition (Steinbrink & Lachmann, 2014). The increasing knowledge of grapheme-phoneme relation influences the progression of phonological awareness and vice versa (Foulin, 2005). As for the *phoneme perception*, a large number of studies demonstrated, that the phonological awareness could predict future reading and writing performance of beginning readers (Heath & Hogben, 2004; Näslund & Schneider, 1996; Wagner et al., 1997; Watson et al., 2003; Wimmer, Landerl, Linortner & Hummer, 1991).

However, the way *phonological awareness* influences reading development is still a subject of research. For example, "the chicken or the egg dilemma"

considering the size of orthographic units in early reading: what was first, the phonemes/graphemes or the syllables? Deavers, Solity and Kerfoot (2000, p. 268) summarized these two approaches as follows:

”On the one hand, small-units-first theories assume a progression from the use of small units (i.e. graphemes and phonemes) to the use of larger units such as rimes (Frith, 1985; Marsh, Friedman, Desberg & Saterdahl, 1981). The alternate view is that the acquisition of literacy skills mirrors that of phonological awareness, proceeding from large units (i.e. onsets and rimes) to small units. The work of Goswami (Goswami, 1990, 1993; Treiman, 1992) has been interpreted in support of large-units-first theories (see Goswami, 1999, for discussion)”.

Phonetic recoding in working memory

The *phonetic recoding in working memory* describes the ability to recode written symbols into a sound-based representational system to maintain them efficiently in working memory (Baddeley, 1979, 1982; Conrad, 1964; Mattingly, 1984). This phonetic recoding can be understood as a speech-based short-term storage, which keeps a phonological information active in mind. Although it is not that important for reading comprehension in skilled readers (Crowder & Wagner, 1992), it may play an important role in reading acquisition as long as grapheme-phoneme relations are not yet sufficiently automatized. Beginning readers need a large investment of resources of working memory to decode a series of visually presented letters, store the sounds of the letters in a temporary store, and blend these memorized sounds into a word (Alloway, Gathercole, Willis & Adams, 2004; Baddeley, 2003; Wagner & Torgesen, 1987). Thus, the better the phonetic recoding in working memory, the more resources are available for the other tasks, especially the blending of sounds into words (Baddeley, 1979, 1982; Torgesen & Houck, 1980).

Since the phonetic recoding in working memory is also included in learning the grapheme-phoneme correspondence, it could also predict future reading and writing skills of beginning readers (Heath & Hogben, 2004; Jorm, Share, Maclean & Matthews, 1984; von Goldammer, Mähler, Bockmann & Hasselhorn, 2010).

Phonological recoding in lexical access

The concept of *phonological recoding in lexical access* describes the ability to decode visual information (e.g., letters, words, symbols, color) into a sound-based representational system (Baron & Strawson, 1976; Coltheart, Davelaar, Jonasson & Besner, 1977; Crowder & Wagner, 1992; Kleiman, 1975; Martin, 1978; Meyer, Schvaneveldt & Ruddy, 1974). The efficiency of this ability can be measured, for example, by rapid naming of objects, colors or words (rapid automatized naming, RAN; Wolf, 1986). Typically, those items are named very fast and accurately (Steinbrink & Lachmann, 2014). However, it is still not clear whether phonological recoding is necessarily involved into the process of transfer from written words to their lexical content (Crowder & Wagner, 1992; McCusker, Hillinger & Bias, 1981; Wagner & Torgesen, 1987). There is evidence for two routes to lexical access (see Chapter 2.2.2). One route, which could be observed in more skilled readers, seems to use a direct pairing of the visual pattern with its lexical content. The other route, which uses phonological recoding, seems to be more important during early stages of reading acquisition or for reading non-words or less familiar words (Baron, 1979; Coltheart, 2007; Doctor & Coltheart, 1980; Ehri, 1979; Stanovich, 1982a, 1982b).

The above described naming task of letters, colors or objects (RAN; Wolf, 1986) could predict future reading and writing abilities of beginning readers, as shown in several studies (e.g., Kirby et al., 2010; Wolf, Bowers & Biddle, 2000). However, there is still a debate about the processes involved in this rapid naming, and thereby, about the validity of the rapid naming test to measure the phonological recoding in lexical access (Kirby et al., 2010; Steinbrink & Lachmann, 2014).

2.1.3. Visual perception and processing

Since this thesis investigates the visual processes involved in letter detection and reading, the visual cognitive bases are described in more detail in the following chapters. Hence, I here just focus on *visual temporal processing*, which features in some theories of *reading disabilities* (see Chapter 2.3).

Visual temporal processing

Hood and Conlon (2004) examined whether *visual temporal processing* could predict the reading development of beginning readers. They assumed that visual temporal processing influences *binocular stability* and *saccades efficiency*, which both influence the encoding of letter positions in words and the global word perception. Their results suggested that the performance of visual temporal processing could be a useful addition to predicting the risk of early reading difficulties, especially in predicting the acquisition of letter knowledge and thereby the orthographic performance (Boets, Wouters, van Wieringen, De Smedt & Ghesquière, 2008).

2.2. Reading acquisition and models of reading

2.2.1. Modells of reading acquisition

In Chapter 2.1.1 I discussed that reading expertise changes the underlying cortical network and that this modification of different brain areas enable specific ways of reading words. Thereby, the specialization of different brain areas does not take place simultaneously, but rather step by step. For example, the development of the ventral circuit is assisted by the dorsal circuit; hence, the dorsal circuit needs to develop first. The above mentioned results provide evidence of a phase model of reading acquisition. Actually, such stepwise models of reading acquisition were suggested many years before modern brain imaging became a mainstay of scientific research.

FRITH'S THREE STEP MODEL OF READING ACQUISITION

Based on the *logogen model* of Morton (1969, 1980), which described different information-processing strategies in skilled readers, Frith (1985, 1986) introduced a *three-step model* of reading and writing acquisition. According to this model, reading development can be summarized into three consecutive phases: the *logographic phase*, the *alphabetic phase* and the *orthographic phase*. Each of them is characterized by the development of specific reading strategies. Thereby, each strategy is based on prior strategies, however, it should be noted, that a follow-

ing strategy does not supersede the previous strategy. Skilled readers can use all acquired strategies, depending on the requirements of different reading contexts. Frith's model of reading development can be transferred to the development of writing ability, however, the phases of reading and writing are not in parallel but rather can be assumed as step-wise interaction between reading and writing development. This interaction will be discussed later; first I want to explain the characteristics of the different phases.

Logographic phase

During the *logographic phase*, reading is mostly based on recognition of salient visual features of a word. Pre-literate children are able to remember logos of companies, for example Coca-Cola. This "reading process" is more driven by the color combination and the typical scripture than by remembering the initial letter "C" and the final letter "a". Actually, those terminal letters can serve as a clue feature, e.g., the final oval in ESSO (Augst, 1986). However, the appearance or correct order of letters is not always necessary to remember a logo. Children which are able to "read" environmental prints, for instance, the logo of PEPSI, fail to notice the change, if one letter is altered (e.g., PEPSI in XEPSI; Ehri, 1995; Masonheimer, Drum & Ehri, 1984). In the same way, the logo of "Harrods" could get identified, if it is written as "Hrorasd" or "HaRroDs" (Coltheart, 1986). Nevertheless, children start to recognize that letters are essential components of written language.

Alphabetic phase

Normally, learning to read starts with alphabet-letter instruction, meaning learning the GPC rules. Children have to learn, that letters are not just essential parts of words, but representing meaningful units of spoken language (i.e., phonemes). Reading during this phase is based on sequential letter-sound by letter-sound analysis (Frith, 1986). Hence, each letter and the order of letters are important to enable beginning readers to blend the decoded phonemes into the whole word. Typically this procedure can be observed in children, when they first translate the single letters into phonemes (e.g., <m> → /m/, <a> → /a/, <m> → /m/,

<a> → /a/), merge those phonemes to syllables (e.g., /m/ and /a/ to /ma/) and connect those syllables until the syllable sequence reminds them to a familiar word (e.g., /'mama/). This sound-blending could sometimes be remarkable, for instance, the sound sequence "cuh-a-thu" which reminds children of the word "cat" (Frith, 1986).

Orthographic phase

The more reading experience of beginning readers increases the larger the units become, which are used for word recognition. Highly frequent letter combinations are combined to joined sound units, for example morphemes (e.g., the prefix "re-" in "remember", "representation" etc. or the suffix "-ing" as part of forming nouns out of verbs). This enables readers to read irregular words, which do not follow exactly the GPC rules. The word "shoe" is no longer read as a combination of single phonemes following the GPC rules /ʃ/+/oʊ/, but as a whole word by sight with correct pronunciation (i.e. /ju:/).

Considering these different phases, it follows that reading develops not gradually (i.e., reading performance becomes better and better), but rather it develops step-wise with qualitative changes of reading strategies (Frith, 1986). Since reading acquisition, actually, is connected with the acquisition of writing skills, we could assume, that the same steps would take place in writing development. However, there are different reasons to suggest that the processes of reading and writing acquisition do not develop in parallel but interact. Frith (1986) expanded her model in a way, that each step in reading acquisition is initiated by a progress in writing skills and vice versa (illustrated in Figure 2.2). For example, the logographic reading strategy precedes the logographic writing stage, whereas the alphabetic strategy is first developed in the writing domain. The latter could be illustrated by the observation that learning to write letter-by-letter strengthens the understanding of the GPC and how written words are constructed. In turn, this understanding of word structure influences the perception of words as a compound string built out of letters, or more exactly, graphemes.

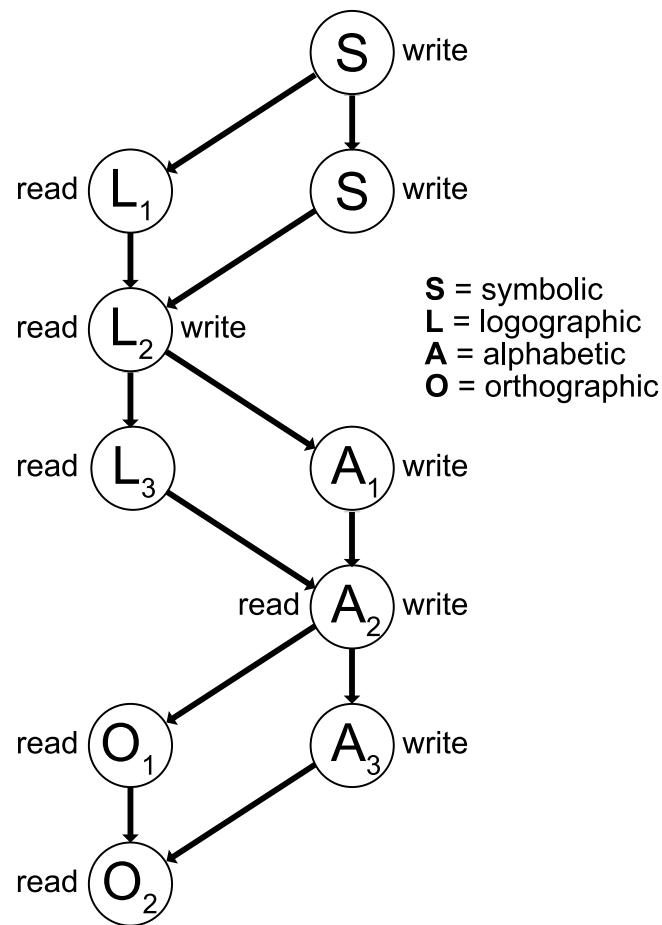


Figure 2.2.: Frith's stepwise model of reading acquisition (adapted from Frith, 1986)

Apart from the simplicity of Frith's three steps model of reading acquisition, one strength is that it can explain the mistakes observed in children and adults with reading disabilities. Hence, I will come back to this model when I illustrate some reasons which are thought to be responsible for developmental dyslexia (Chapter 2.3).

EHRI'S MODEL OF SIGHT WORD READING

Ehri (1995) took up Frith's model and improved it by inserting an additional phase – the *partial alphabetic phase* – which can be understood as a transition stage

between the logographic and alphabetic phases in Frith's model. Furthermore, she replaced the original terminology introduced by Frith (1985, 1986) to avoid confusion from different usages of these terms in different contexts (Ehri, 1995). Her *pre-alphabetic phase* closely resemble the *logographic phase*, her *full alphabetic phase* corresponds the *alphabetic phase* and her *consolidated alphabetic phase* can be understood as Frith's *orthographic phase*. Ehri (1995) used her model to explain different reading strategies, which could be observed in whole word reading¹.

In parallel to Frith (1985, 1986), Ehri (1995) emphasized that whole word reading in skilled readers is different from *visual clue reading* (similar to the *logographic strategy*), which is used in the **pre-alphabetic phase** (Ehri & Wilce, 1985). During this phase of reading acquisition, words are perceived and recognized as a whole structure, without considering a letter-sound relation. Sometimes letters even play no role to remember a logo. Thus, for example, a thumbprint, which is presented after a word, could serve as a salient visual cue (Gough, 1996). Letters could also serve as visual cues, but rather because of their visual features (e.g., the two humps in the middle of "camel"; Gough, 1996) than their phonological meaning.

Ehri and Wilce (1985) demonstrated, that for beginning readers, who were assumed to be in the pre-alphabetic phase, it was easier to remember a word with unique visual cues (e.g., "WcB" for "elephant"), whereas for more advanced readers, it was easier to read words, if those contain salient cues linking letters to sounds (e.g., "LFT" for "elephant"). In parallel to the *visual cue reading* this strategy could be called *phonetic cue reading*.

Therefore, Ehri (1995) proposed a **partial alphabetic** phase in which letters, as indicators of word recognition, become more important. During this stage, letters are perceived as typical parts of a specific word, symbolizing sounds in that word. Children start to recognize that similar sounding words consist of more or less the same letters, and are able to identify some words because of salient cue letters.

¹Originally, Ehri (1995) used the term "sight word reading". I prefer the term "whole word reading" (e.g., Coltheart, 1986) to underline the difference to the perceptual process of letter detection.

The GPC rules are acquired during the full **alphabetic phase**. Readers start to understand the rules of the conventional spelling system, and thereby, that most graphemes symbolize specific phonemes in spoken language (Venezky, 1970). This understanding enables them to transform unfamiliar spellings of words into blended pronunciation. With increasing reading experience, more and more letter patterns become consolidated. This enables readers to directly recognize larger units in words including more than single letters (e.g., morphemes, syllables or rhymes) and results, according to Ehri (1995), in the consolidated alphabetic phase.

This **consolidated alphabetic phase** is Ehri's equivalent to the *orthographic phase* (Frith, 1985, 1986). During this stage, readers include these multi-letter patterns to their generalized knowledge of the spelling system and enable them for whole word reading. However, compared to the pre-alphabetic phase skilled readers do not perceive words as a whole structure anymore. Instead of searching for salient visual cues, they perceive words as a combination of graphemes, morphemes and syllables.

It should be noted, that both models are elaborated for Anglo-American languages, which use a more intransparent orthography compared to the transparent orthography as used in German. In parallel to what I discussed for the neuronal bases of reading, it can be assumed, that also reading development differs for languages and orthographies. Thus, the models discussed above cannot be transferred completely to the reading development of beginning readers of German (Scheerer-Neumann, 2006; Wimmer & Hummer, 1990). However, most models which try to explain the reading development for German orthography, are influenced by and refer to those of Frith and Ehri (e.g., Günther, 1986; Scheerer-Neumann, 2006).

Ehri (2007) emphasized the important role of automaticity and speed for reaching advanced reading skills. Whereas Chall (1983) predicted the development of reading speed as a part of the medial stages of reading acquisition, Ehri (1998) assumed that automatization takes place after all other stages, and enables readers to read more and more words fluently. There is evidence in support of both ideas. Although even in first graders an automatically processing of familiar words was observed (Guttentag & Haith, 1978), their reading-speed depended significantly on word length. For experienced readers this *word-length-effect* for familiar words

vanished (Samuels, LaBerge & Bremer, 1978), what is caused by a higher degree of *unitization* (Ehri, 1983). This means that familiar words are read as one unit rather than as a combination of phonemes, morphemes and syllables. Increasing automatization enables readers to switch their attention more and more from word decoding to text comprehension (LaBerge & Samuels, 1974; Samuels & Kamil, 1984). This process of automatization is the main topic of the following model.

READING ACQUISITION AS FUNCTIONAL COORDINATION

Learning to read involves the development of specialized letter specific processing strategies, which were described as *analytical* (van Leeuwen & Lachmann, 2004). In contrast, the earlier developed object recognition strategies were assumed to be more *holistically*. Characteristics of these two strategies are explained in the following chapters. The development of these letter specific strategies is part of a process of *functional coordination* (Lachmann & van Leeuwen, 2014). This four stages modeling framework (see Figure 2.3) describes the process of reading acquisition as a kind of procedural learning (Heim et al., 2010; Nicolson & Fawcett, 2011).

In the first stage, the *recruiting stage*, pre-existing skills are recruited to learn characteristics of specific letters and written language. Basic visual object recognition skills (*cognitive functions*) enable beginning readers to discriminate two-dimensional line drawings (i.e., letters), which are the basic components of written language. Motoric skills are required to draw these new shapes and thereby to internalize the specific structure of individual letters. During the second stage these skills become modified (*modification stage*). This modification enables beginning readers to pay attention to specific features of letters, which are irrelevant for object recognition. For instance, whereas orientation is less important in object recognition, it is crucial for letter. In the same way, symmetry generalization has to be suppressed for efficient letter processing. Hence, this modification is driven by the emergence of an analytical preference for letters. At the same stage of reading acquisition, skills concerning the phonological systems get improved; for instance, an improvement in phonological awareness (Blomert, 2011; Fernandes, Vale, Martins, Morais & Kolinsky, 2014; Lachmann, 2002; McBride-Chang, 1999).

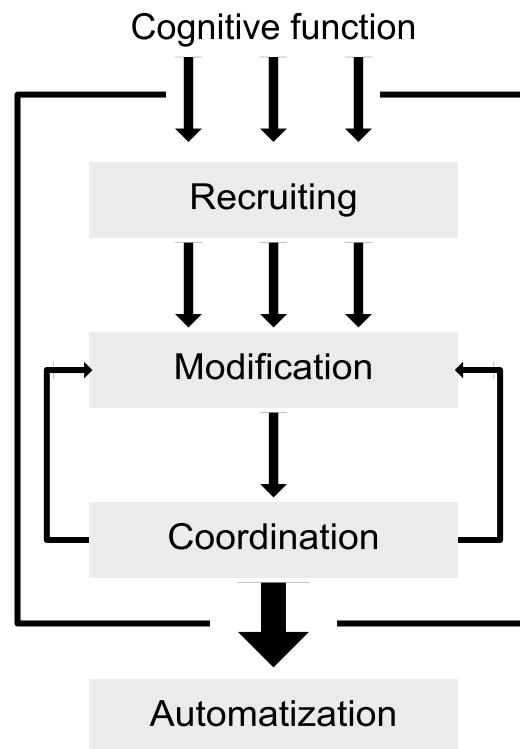


Figure 2.3.: Illustration of the functional coordination model (adapted from Lachmann & van Leeuwen, 2014)

Based on these modifications, during the third stage (*coordination stage*) the specific visual and phonological processing skills get functionally coordinated, leading to a cross-modal representation of letters, which include the GPC rules. The last stage (*automatization stage*) is characterized by a long-term training, in which the usage of the modified skills and connected strategies becomes more and more automatized (Lachmann & van Leeuwen, 2008b). This automatization takes several years, although beginning readers are able to read relatively fast and show an established representation of the GPC rules (Froyen, Bonte, van Atteveldt & Blomert, 2009).

2.2.2. Models of reading aloud

Models of reading aloud could be grouped in two main categories, depending on the underlying theoretical assumption: *connectionist* and *non-connectionist models*.

Connectionist models are more neuron-like network models of reading, which are biologically inspired from the way how information is memorized in and recalled from our brain. They predict that reading letters, morphemes and syllables up to whole words activate specific patterns of neuronal networks, which retrieve phonological and semantic information from long-term memory (e.g., Plaut, 1996; Seidenberg, Petersen, Macdonald & Plaut, 1996). Connectionist models assume one level which operates between orthographical, phonological and semantic contents. Hence, written words are converted into speech, based on direct links between patterns of orthographic input and phonological output. Obviously, for regular as well as for irregular words this enables fast word reading, depending on the degree of familiarity. Furthermore, reading of unfamiliar words or non-words can be explained by activation of typical phonological patterns for familiar words, which are similar in orthography. Since these connectionist models are explicitly based on specific memory encoding and decoding processes, they include learning processes. Therefore, they can be used to explain findings for adult reading as well as for reading development. However, their explanatory power is limited, when trying to explain reading impairments which are acquired by injury of specific brain areas (Snowling & Hulme, 2007), after stroke or as a result of mental diseases.

Non-connectionist models predict different, more or less independent routes, which enable sequential word reading by following the GPC rules on the one hand, and on the other hand by retrieving the pronunciation of whole words or at least word segments as one structure from a mental dictionary. This distinction can explain different observations for reading familiar words as well as unfamiliar or non-words. One strength of this model is the possibility to explain different kinds of reading disabilities, which could occur in adults after brain damage. Though, the influence of learning is not explicitly integrated into this model, in contrast to the connectionist models. Thus, it is not that successful to explain developmental aspects of reading and reading disabilities compared to the connectionist models.

In sum, both approaches have their strengths and weaknesses in different contexts; however, during the last decades both models have developed in converging ways (Steinbrink & Lachmann, 2014). Since the following studies are more

connected to single letter processing and non-word reading, I will take a closer look to the dual-route theory of reading, in particular, the dual-route-cascade model (DRC; Coltheart, Rastle, Perry, Langdon & Ziegler, 2001).

THE DUAL ROUTE MODEL OF READING

The idea that at least two ways for word reading are available, reaches back to the beginning of the 20th century. De Saussure (1922) differentiated between reading familiar words and unknown words. Letters are decoded letter-by-letter, whereas the first ones are decoded as a whole shape (see translation in Coltheart, 2007).

This idea was improved during several intermediate stages (e.g., Baron & Strawson, 1976; Forster & Chambers, 1973; Marshall & Newcombe, 1973) and resulted in modern *dual-route models*, in which two strategies are processed in parallel. In addition to earlier models, these modern models do not just differentiate between words and non-words; they explain how reading of unfamiliar or non-words integrates some typical pronunciation features which differ from simple GPC rules by considering larger multi-letter units. For example, the non-word "wought" could be pronounced similar to "thought" instead of just following the GPC rules. Furthermore, these modern models integrate a context-dependency, which also is available in spoken language, for instance, to distinguish homophones (e.g., "pair" vs. "pear"; Baron & McKillop, 1975).

Coltheart (1980) differentiated between a *lexical* and a *non-lexical* route, which are processed in parallel for reading familiar as well as unfamiliar and non-words. The *lexical route* retrieves information of pronunciation from a mental lexicon or dictionary. Independently, whether familiar words are pronounced in a regular or irregular way, they profit from the *lexical route* in which the pronunciation gets recalled from the mental lexicon. This requires that the word was previously stored in this lexicon, and therefore, this route only works for real words. Reading via the *non-lexical route* is based on a step-by-step decoding of graphemes into phonemes and merging these phonemes into blended pronunciation. Hence, usage of this route is not restricted to real words, in fact, the *non-lexical route* does not distinguish whether the word is an unfamiliar real word or a non-word. Coltheart (2007) emphasized, that the *non-lexical route*, in contrast to earlier models,

uses graphemes as orthographical segments instead of letters. Thus, the *non-lexical route* uses an algorithm based on the GPC rules, for instance the two graphemes <th> and <igh> forming the word "thigh", are transferred via the GPC rules to the phonemes /θ/ and /ai/ and merged to a blended pronunciation /θai/.

Particularly in intransparent orthographies, in which irregular words do not strictly follow the GPC rules, both routes deliver different results. This raises the question how these two routes are related.

In general, there are two possible ways how these two routes could be processed in parallel. Earlier models assumed a so-called *horse-race model*, meaning that both routes start at the same time and are processed independently; the pronunciation output depends on which path finishes first. Though, this model could not explain why unfamiliar irregular words mostly are pronounced in the correct way. For unfamiliar words, one would expect, that the non-lexical route wins the race, because no information can be retrieved from the mental lexicon. This would lead to regularization errors, meaning that the word would be pronounced strictly confirming to the GPC rules. However, as can be seen in different studies, responses to the irregular words are rather slow but correct (Coltheart, 2007). In accordance with these results, Baron (1977) suggested a *hose-and-bucket model*, described in the following way:

"If we imagine the both paths as hoses that can be used to fill up a bucket with information about meaning, we can see that addition of a second hose can speed up filling the bucket even if it provides less water than the first." (Baron, 1977, p. 203)

This *hose-and-bucket* analogy illustrates how both routes influence simultaneously the reading processes. The strength of both routes is not fixed but varies, depending on requirements of the specific task. Nevertheless, both routes are involved in the derivation of the correct pronunciation. This assumption of interacting routes moves the dual-route models closer to the direction of the non-connectionist models of reading.

Today, the dual-route-model of Coltheart (1980) exists in an extended version, the *dual-route cascaded* (DRC) model (Coltheart, Curtis, Atkins & Haller,

1993; Coltheart et al., 2001). Cascaded means that between visual input of words and letters and the phonological output, different steps have to be passed, which are connected and could either activate or inhibit the following steps. The reason for this extension was to develop the dual-route model into a *computational model*, in order enable a quantitative test of its predictions. On the one hand, this possibility could underline the explanatory power of the model and show how well predictions of the model fit to the reality. On the other hand, it could amplify our understanding, how different conditions influence or even disturb the reading process.

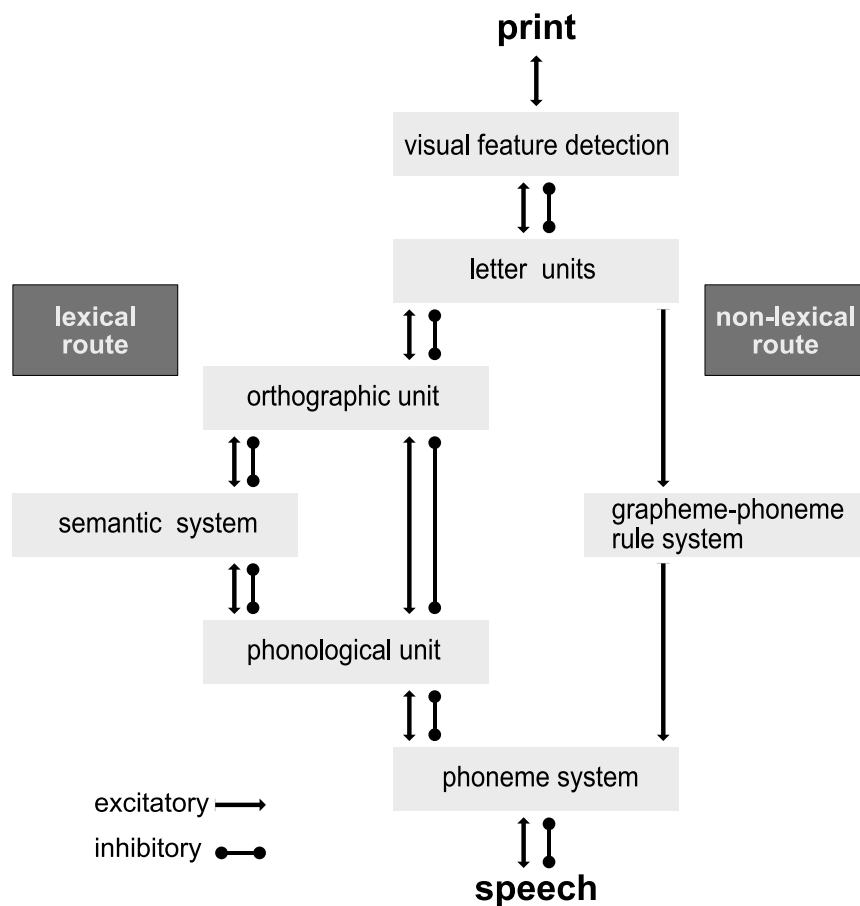


Figure 2.4.: Scheme of the dual-route cascade model of Coltheart et al. (2001). All steps, except those on the non-lexical route, activate or inhibit each other.

In the DRC model (Figure 2.4), first the visual features of word units are analyzed, followed by an activation of those specific letter units, which contain the detected visual features. *Letter units*, which do not contain these features are inhibited. Afterwards, those abstract letter units are processed in the two different routes. The *non-lexical route* (Figure 2.4, right path) transfers these letter units into phonemes strictly from left to right by applying the GPC rules. These phonemes are merged in the *phoneme system* into blended pronunciation. There is no inhibition in the non-lexical route. In the *lexical route* (Figure 2.4, left path) the letter units activate abstract word clusters in an *orthographic lexicon*, which again activate the memorized pronunciation in the *phonological lexicon*. However, this latter activation is also modulated by a *semantic system*, which contains information about the meaning of words. This enables the lexical route to integrate context sensitivity and benefits word pronunciation, which is in accordance with the semantic system, whereas pronunciation which is not in accordance with this system is inhibited. This context dependency is particularly important for correctly reading words that include identically spelled but differently pronounced letter groups, as for instance "ough" in "though" (pronounced /oʊ/ as in **toe**), in "tough" (/ʌf/ as in **cuff**) or in "through" (/u:/ as in **blue**).

Inhibition is an important factor within the *lexical route*, in order to avoid pronunciation mistakes and instead enables a restart or an interruption of the lexical route. The final pronunciation is again generated in adjustment with the *phonological system*. Since both routes are connected via the *letter units input* and the *phonological system output*, they are not independent but in interaction with each other. The input to the lexical route can activate or inhibit the output of the non-lexical route and vice versa.

A strength of the DRC model is, that it explains a range of findings in the context of word and non-word reading, some of which will be discussed in the following.

Forster and Chambers (1973) demonstrated a *frequency effect*, meaning that high-frequent words are read faster than low-frequent words. The DRC model could explain this effect as resulting from a more established representation of high-frequent than low-frequent words in the orthographic lexicon, resulting in faster activation for the former. A similar explanation applies to the observation

that regular words are processed faster than non-words (e.g., McCann & Besner, 1987; Rastle & Coltheart, 1999b). The regular words are received directly from the orthographic lexicon, in contrast to the non-words, which merely are activated by using the GPC rules in the non-lexical route. Therefore, it is obvious that reading non-words took longer the more graphemes have to be transferred into phonemes, resulting in a *word length effect* in non-words and unfamiliar words (e.g., New, Ferrand, Pallier & Brysbaert, 2006).

High-frequent regular words as well as high-frequent irregular words would have their response latencies determined entirely by a fast process through the lexical route, whereas for low-frequent words the regular words additionally benefit from the non-lexical route. Therefore, for low-frequent words reading is faster for regular than for irregular words. This *regularity advantage* decreases with an increase of frequency (Paap & Noel, 1991; Seidenberg, Waters, Barnes & Tanenhaus, 1984; Taraban & McClelland, 1987). The regularity advantage for low-frequent words also decreases, depending on how much graphemes in the irregular words follow the GPC rules (Rastle & Coltheart, 1999b). The more graphemes in irregular words follow the GPC rules, the more they could profit from the non-lexical route. In turn, *pseudohomophonic non-words*, which are similar to real words, profit from the lexical route in contrast to *non-pseudohomophonic non-words*, which do not comply with any real word (McCann & Besner, 1987; Seidenberg et al., 1996; Taft & Russell, 1992).

Many studies demonstrated that non-words which are presented in-between regular words are read faster than non-words which are neighbored by irregular words (see Andrews, 1997, for a review). This could be explained by a higher pre-activation of the lexical route in the first case. Participants are primed to use the non-lexical route and fade out the lexical route. A similar priming effect could be observed, when participants subsequently read two phonological identical words (Rastle & Coltheart, 1999a).

Coltheart et al. (2001) demonstrated that their computational model of the DRC model fits these findings very well. Additionally, they simulated some findings in acquired dyslexia after brain injury. Some examples are discussed in Chapter 2.3. Since the lexical route plays a more important role in intransparent orthographies which contains more irregular words, we could assume, that the

model has to be modified to make predictions for more transparent orthographies, in which the non-lexical route, at least for beginning readers, should play a more important role. Ziegler, Perry and Coltheart (2000) demonstrated that with slight modification of variables in their computational model, the DRC also fits very well for more transparent orthographies, such as the German one.

2.3. Reading disabilities

Models of reading acquisition emphasize the role of different reading acquisition stages. Each reading strategy, which is characteristic for a specific phase, must be sufficiently automatized to reach the next phase. Although an insufficient strategy can be compensated to a certain degree, lack of automatization leads to reading difficulties (Ehri, 1995, 2007; Frith, 1985; Lachmann, 2002). In the same way, the models of reading (e.g., the DRC model) predict how disturbance of a specific route or strategy raises reading difficulties (Coltheart, 2007). Hence, on the one hand, these models can make some predictions about the appearance of reading disabilities. On the other hand, the development of these models of reading and reading acquisition is driven by findings regarding different reading difficulties in people with developmental and acquired dyslexia. *Developmental dyslexia* is mostly diagnosed in reading beginners and means a learning disorder, which influences a proper reading acquisition. It is guessed that 10% to 15% of all children in school are concerned of this disorder (Lyon, Fletcher & Barnes, 2002; S. E. Shaywitz, Escobar, Shaywitz, Fletcher & Makuch, 1992). In contrast, *acquired dyslexia* means the loss of a formerly properly developed reading ability, mostly observed in adults after brain damage.

2.3.1. Diagnostic procedure

The diagnosis of reading disabilities (*dyslexia*) is based on different pathological dimensions: *symptoms*, *pathogenesis* (development) and *origin* (Steinbrink & Lachmann, 2014). Since *acquired dyslexia* normally is caused by brain injury, it is not described separately within the common diagnostic manuals (e.g., ICD-10, DSM-5). It is just listed under symptoms which are not elsewhere classified (ICD-10,

R48.0). *Developmental dyslexia* is characterized as developmental disorder, exactly as *specific reading disorder* (ICD–10, F81.0). It is described as follows:

”The main feature is a specific and significant impairment in the development of reading skills that is not solely accounted for by mental age, visual acuity problems, or inadequate schooling. Reading comprehension skill, reading word recognition, oral reading skill, and performance of tasks requiring reading may all be affected. Spelling difficulties are frequently associated with specific reading disorder and often remain into adolescence even after some progress in reading has been made. Specific developmental disorders of reading are commonly preceded by a history of disorders in speech or language development. Associated emotional and behavioral disturbances are common during the school age period.” (World Health Organization, 1992, p. 245)

To summarize, developmental dyslexia involves specific reading difficulties, which could not be explained by other disorders. It is often correlated with or preceded by difficulties in other domains (e.g., language processing and emotional domains), and symptoms decrease within the adolescence but mostly do not completely disappear.

These criteria can be understood as necessary conditions to diagnose reading disorders; however, these criteria are formulated rather vaguely. Hence, in clinical and research contexts, some more restrictive criteria are used. Besides ones that should exclude other sources causing the same symptoms, mostly, a criterion of “*double discrepancy*” is used to diagnose reading disorder. Double discrepancy means that the value of reading ability is at least two standard deviations beyond the mean, which would be expected for the chronological age and intelligence (Steinbrink & Lachmann, 2014). By default, this discrepancy is determined by tests measuring intelligence, reading accuracy and reading speed.

2.3.2. Theories of dyslexia

Since an early remediation attenuates the effect of developmental reading disabilities, potential predictors were subjects in a wide range of research (e.g., Bowers,

Golden, Kennedy & Young, 1994; Fletcher, Foorman, Shaywitz & Shaywitz, 1999; Liberman & Shankweiler, 1979; Snowling, 2000; Vellutino, 1979; Wagner, Torgesen & Rashotte, 1994; Wolf et al., 2000; Wolf, Pfeil, Lotz & Biddle, 1994). These studies showed, that developmental dyslexia cannot be understood from a limited number of predictors, but that the group of dyslexics is rather heterogenous. Dyslexics differ in their symptoms concerning different aspects of written language processing.

Early theories of reading disorders proposed a deficit in the *visual domain*, which leads to what they called "congenital word blindness" (Hinshelwood, 1917). These visual deficits were ascribed to be a result of neurodevelopmental disorders or delays. Orton (1925) suggested that deficits in the development of hemispheric dominance impede proper letter detection, which leads, for instance, to mirror errors (e.g., b, d, p and q are perceived as the same symbol). Although these errors seem to be very frequently in children diagnosed with developmental dyslexia, a lot of studies showed, by controlling the influence of linguistic processing, that dyslexics and children with normal reading skills do not differ significantly in their general visual abilities (e.g., Fletcher et al., 1999; Snowling, 2000; Vellutino, 1979). Thus, these abilities are poor predictors for performance in word identification, spelling, pseudoword decoding and reading comprehension (Vellutino, 1979; Vellutino & Fletcher, 2007).

The *magnocellular deficit theory* (e.g., Stein, Talcott & Witton, 2001, see also Stein, 2002, for a review) accommodates the observation that also auditory, phonological skills are involved in reading. This theory predicts a deficit in visual information processing, based on magnocellular dysfunctions in dyslexics (Badcock & Lovegrove, 1981; Breitmeyer, 1989; Lovegrove, Martin & Slaghuis, 1986; Stein et al., 2001). The *magnocellular system* is supposed to be responsible for the suppression of unwanted movements and rapid changes in the visual field. Hence, its dysfunction in dyslexics leads to greater fluctuations in the visual system and thereby to masking effects (Badcock & Lovegrove, 1981; Lovegrove et al., 1986), which impair fluent reading of connected text. This deficit was demonstrated in electro-physiological studies (Lehmkuhle, Garzia, Turner, Hash & Baro, 1993; Livingstone, Rosen, Drislane & Galaburda, 1991) and was observed in eye-movement studies, showing different patterns of eye-movement in dyslexics and normally

skilled readers (Biscaldi, Gezeck & Stuhr, 1998; Eden, Stein, Wood & Wood, 1994; Fischer & Hartnegg, 2008). Since this deficit negatively affects automatization, it impairs the development of grapheme-phoneme mapping, and thereby, a proper development of phonological awareness and phonological representations.

Besides some results showing that poor reading performance often can get explained with a general deficit in a sufficient vocabulary (Dickinson & Tabors, 1991, 2001; Snow, Barnes, Chandler, Goodman & Hemphill, 1991; Tabors & Snow, 2001), today, most theories propose a deficit in the phonological domain, especially in phonological awareness, which impairs a proper acquisition of grapheme-phoneme mapping (Bowers & Wolf, 1993; Fletcher et al., 1999; Liberman & Shankweiler, 1979; Snowling, 1980, 2000; Wagner et al., 1994; Wolf et al., 1994). Most children with reading disabilities show weaker performance in tests measuring sensitivity to rhyme, phoneme segmentation and sound blending (Vellutino & Fletcher, 2007). Likewise, dyslexics show deficits in *orthographic knowledge*, meaning the knowledge of orthographic regularities, for instance, the double consonant after a short vocal in the German orthography (e.g., <mm> in "kommen"). This *orthographic knowledge* is important to reduce working memory load to enable a sufficient automatization of word recognition (Ehri, 1999). Both, knowledge of GPC and orthographic knowledge are important conditions to establish whole word reading strategies.

Reading disabilities as a deficit in functional coordination

Whereas most theories of reading disabilities focus on possible deficits in a specific domain which causes reading difficulties, Lachmann (2002) described an approach focusing the interaction of basic skills and sub-functions, which are involved in the reading process. In the *functional coordination deficit model* (FCD) the failure of sufficient automatization and optimal integration of reading related information plays a crucial role in the explanation of reading disabilities. Hence, reading difficulties can be caused by disturbances during different stages of the formerly described functional coordination model of reading acquisition (see Chapter 2.2.2). Deficiencies of preliminary skills of reading, for instance, lacking auditory abilities (Ahissar, Protopapas, Reid & Merzenich, 2000; Goswami, 2011; Groth, Lachmann, Riecker, Muthmann & Steinbrink, 2011; Hämäläinen, Salminen & Leppänen, 2013;

Richardson, Thomson, Scott & Goswami, 2004; Talcott & Witton, 2002), visual instabilities (Becker, Elliott & Lachmann, 2005; Slaghuis & Ryan, 1999; Stein, 2002; Stein et al., 2001) or combinations thereof (Au & Lovegrove, 2007; Farmer & Klein, 1995) influence the recruitment of principle letter concepts in the first stage of reading acquisition. Although the lack of these abilities may be masked by compensating strategies (Frith, 1986), it impairs a proper coordination in the following modification stages. This could be observed in dyslexics, in which failure to suppress symmetry or other holistic strategies (e.g., Pegado, Nakamura, Cohen & Dehaene, 2011; Perea, Moret-Tatay & Panadero, 2011; von Károlyi, Winner, Gray & Sherman, 2003) lead to problems in developing phonological (e.g., Snowling, 2001; Stein, 2012) or orthographic skills (Seymour & Evans, 1993).

The lack of optimal coordination between the visual and auditory domain can explain these errors. Using the example of mirror errors, Lachmann (2002) explained that not principal deficits in the visual domains cause these errors (see Orton, 1925), but that they are the result of an insufficient modification of earlier developed object recognition strategies. Typically, symmetrically related objects activate the same neuronal network, as a result of a learning process during childhood, to ensure object constancy (see Corballis, 1988; Jolicoeur, Corballis & Lawson, 1998; Klatzky & Stoy, 1974; Kuehn & Jolicoeur, 1994). This symmetry generalization has to be suppressed for letters. For instance, the letters "b" and "d" are mirror images to each other and therefore should be represented with the same pattern of neuronal activity. However, in skilled readers those symbols are connected with phonological information and therefore are represented with a non-ambiguous neuronal network in the brain, which presents the GPC. Hence, an optimal and automatized coordination between the visual and auditive domain, on the one hand, enables reading beginners to connect graphemes with phonemes during reading acquisition, and on the other hand, enables more advanced readers to decode quickly and accurately graphemes into phonemes. In contrast, dyslexics have difficulties to suppress this symmetry and therefore retrieve ambiguous phonological information, leading to the observed mirror errors.

On the one hand, a general deficit in functional coordination between auditive and visual information impairs a sufficient phoneme-to-grapheme encoding in earlier stages of reading acquisition, in which the actual coordination process took

place (Froyen, Willems & Blomert, 2011). On the other hand, reading disabilities can result from an impairment of automatization of the graphemes-to-phoneme decoding in later stages (Nicolson & Fawcett, 2011).

2.3.3. Developmental dyslexia

Castles and Coltheart (1993) predicted two types of developmental dyslexia: *Phonological developmental dyslexia*, which causes difficulties in using the non-lexical route as a result of an insufficient grapheme-to-phoneme decoding, and *surface developmental dyslexia*, which impairs a direct requirement of lexical content on the lexical route. As shown in the DRC model (Chapter 2.2.2) this differentiation is more appropriate for *acquired dyslexia* (Coltheart, 2006, 2007). The approach of Bowers and Wolf (1993), assuming a distinction in the domains of phonological awareness and naming-speed, seems to tend in the same direction (see also Bowers et al., 1994; Wolf et al., 2000, 1994). Since neither of these theories could explain all facets of dyslexia, Morris et al. (1998) tried to combine all approaches to one classification model of reading disabilities. They extracted seven subtypes of dyslexia, considering different combinations of variables which could explain difficulties in reading. Five subtypes, which show specific reading disabilities, and two subtypes of dyslexics, which show deficits in general written and additional spoken language processing. One of these subtypes only showed deficits in the rate of processing, for instance, in rapid naming tasks. All other subtypes shared deficits in phonological awareness, but differed in their combination of rapid naming, verbal short term memory and general language deficits, such as poor vocabulary (Vellutino & Fletcher, 2007). Although this model is not able to make predictions concerning the development of a single child which is diagnosed as having reading difficulties, it seems to be an appropriate model to accommodate the heterogeneity of developmental dyslexia.

2.3.4. Acquired dyslexia

For *acquired dyslexia* the classification is much clearer, because the implications of different types can mostly get ascribed to an impairment of specific brain regions

(Lambon Ralph & Patterson, 2007; Patterson & Lambon Ralph, 1999). In accordance to the related literature, Lambon Ralph and Patterson (2007) classified four types: a) pure alexia, b) surface dyslexia, c) phonological dyslexia and d) deep-phonological dyslexia.

Pure alexia is marked by an impairment of whole word recognition. Words could only be decoded letter-by-letter, independently from word frequency and orthographic transparency, hence, pure alexia leads to an over-regularization of irregular spelled words. This gave evidence that in pure alexia brain regions are affected, which support a recall of lexical information on a direct path from the mental dictionary. That means the lexical route in the DRC model is affected (Coltheart, 2006).

Surface dyslexia can be described as a milder form of pure alexia. Surface dyslexics also show less impairment in the non-lexical route; reading of regular words and non-words is within a normal range. However, in contrast to pure alexia the over-regularization only is observed for low-frequent words, whereas high-frequent words still profit from the recall from the mental dictionary. Hence, it is assumed, that not the lexical route per se is impaired, but the orthographic or semantic lexicon (see Patterson & Hodges, 1992; Shallice, Warrington & McCarthy, 1983). Since the efficiency of the lexical route is correlated with word frequency, high-frequent words are less affected than low-frequent ones (Coltheart et al., 2001).

Other types of acquired dyslexia in which the non-lexical route is impaired, are described as *phonological dyslexia* or in its strongest form as *deep-phonological dyslexia* (Friedman, 1996; Glosser & Friedman, 1990). In this case, familiar real words are read efficiently across the lexical route, independently whether the word is spelled in a regular or irregular way. Instead, phonological dyslexics are impaired to read unfamiliar or non-words. Particularly in deep dyslexia, there is a tendency to confound morphologically related words (e.g., "lovely" is read as "love") or visually similar words (e.g., "signal" is read as "single"; Lambon Ralph & Patterson, 2007). In the DRC model, this findings are explained by damage of brain regions which are essential for print to speech conversion via the grapheme-phoneme-correspondence rules (Coltheart, 2007).

Summarizing, these findings of prior research in the field of reading disabilities do not just give evidence for possible explanations of reading difficulties, but rather extend our understanding how reading works in normally skilled readers. An insufficient development of different stages during reading acquisition and a lack of automatization explain many findings in developmental dyslexia. In turn, this reflects the strength of these underlying models and show how well they fit with the real mechanisms of reading acquisition. The dual-route models of reading could get substantiated with findings in acquired dyslexia, showing that different brain regions promote the performance of distinct reading strategies, providing a neuronal foundation to these theoretical models.

2.4. Congruency effects in letters and non-letters

In Chapter 2.2 I introduced models of reading and reading acquisition. Both approaches predict specific processing strategies, which are essential for fluent reading. On the one hand, they assume strategies or routes, which enable skilled readers to decode instantly larger word units or even whole words. On the other hand, they assume strategies or routes to read words by decoding single graphemes into phonemes and blending those phonemes to a fluent pronunciation. This grapheme-phoneme decoding presupposes the detection of letter specific features. Letters have to be recognized and discriminated. Since some letters are closely similar it is obvious, that fast letter identification requires specific strategies, which were subject of many studies (e.g., Fernandes & Kolinsky, 2013; Fernandes et al., 2014; Lachmann & van Leeuwen, 2004, 2007, 2008a; Massaro, 1998; McClelland, 1976; van Leeuwen & Lachmann, 2004). Today, these letter specific processing strategies are believed to be acquired during reading acquisition and to differ from the earlier developed object recognition strategies (Lachmann & van Leeuwen, 2014). This assumption is in accordance with prior studies, which demonstrated that letters and non-letters are processed by different systems, especially in early stages of reading acquisition (e.g., Burgund & Abernathy, 2008; Green, Hammond & Supramaniam, 1983; Maurer, Brem, Bucher & Brandeis, 2005; Maurer et al., 2006). On a low-level processing three stages of the letter recognition are differentiated according to Oden (1979).

”The *feature evaluation operation* determines the degree to which each feature is present in a given stimulus; the *prototype matching operation* determines how close each candidate letter pattern comes to providing a match to the stimulus; and the *pattern classification operation* compares how well each letter matches the stimulus relative to the goodness of match for the other letters” (Oden, 1979, p. 340)

This bottom-up process can be understood as a primary form of letter processing. With increasing reading experience, this process gets complemented and replaced more and more by a top-down process, which involves amongst others, especially, integration of larger letter units (e.g., morphemes or syllables) and semantic content (Coltheart et al., 2001; Massaro, 1998; McClelland, 1976). However, in order to understand the higher cognitive processes, which are involved in reading, several studies investigated the influence of letter recognition processes, which are more related to these general bottom-up processes. One of these research topics involve *congruency effects* in contextual embedded letters and non-letter shapes. Those tasks are also known as flanker tasks, because the targets are flanked or surrounded by distractor shapes. *Congruency effect* means, that, for instance, a surrounding shape influences the reaction time for detection of the surrounded target, depending on the degree of similarity in their geometrical features.

These congruency effects principally can be explained by *lateral masking* (Estes, 1972). For large stimuli or stimuli which are presented peripherally, the effect of similarity between the target and the surrounding (or flanker) is possibly caused by an insufficient resolution for peripheral vision. However, disturbance from the distractor was still observed for increased separations between target and distractor; for peripheral (Bouma, 1970; Hagenaar & van der Heijden, 1986; Miller, 1991; Toet & Levi, 1992) as well as central presentation (Leat, Li & Epp, 1999). Since the lack of discriminability between target and surrounding is not sufficient as explanation, *lateral masking* assumes interaction at the local features of the presented objects, leading to *negative congruency effects* for similar shapes (Estes, 1982). That means, that target detection of surrounded shapes is more difficult, if the surrounding is similar to the target. This is in accordance to several studies (e.g., Bavelier, Deruelle & Proksch, 2000; Briand, 1994; van Leeuwen &

Bakker, 1995), which demonstrated larger detection times for targets, surrounded by similar shapes, compared to targets, surrounded by less similar ones. In turn, for an intermediate target-flanker similarity the effects are decreased (Estes, 1982).

These results are in contrast to other studies, showing *positive congruency effects*, meaning that target detection benefits from a higher similarity between targets and flankers. Targets, which are surrounded by congruent shapes (i.e., same geometrical properties as the target) are detected faster than targets with an incongruent surrounding (i.e., different geometrical properties as the target; e.g., Eriksen & Eriksen, 1974). These findings are typical for less complex stimuli.

This contradiction leads to the assumption, that congruency effects may not just be explained by simple feature-interaction. Actually, an influence of attentional processes and late response competition has to be considered (Rueckl, Suzuki & Yeh, 1991; Sanders & Lamers, 2002). For target detection, the attention to the competing distractor has to be suppressed, which is more difficult for similar shapes than for different ones, particularly for more complex targets. Hence, for more complex stimuli the task becomes more difficult and this active suppression of context features leads to a negative congruency effect. In contrast, for less complex stimuli the task is easier and the attention is not only focused on the target stimuli (Lavie, 1995; Treisman & Gelade, 1980). Therefore, different features of the target and the surrounding lead to a response conflict, and thus, to a positive congruency effect (Lachmann, 2007).

Nevertheless, as shown in several studies, these congruency effects seem to differ between letters and non-letters (Fernandes et al., 2014; Lachmann & van Leeuwen, 2004, 2008a; van Leeuwen & Lachmann, 2004). This distinction does not just depend on the identity of the used stimuli. For example, studies which demonstrated a distinction of the influence of symmetry for letter and non-letter perception showed that this distinction varied depending on the task (Lachmann & Geissler, 2002; Lachmann & van Leeuwen, 2004). Hence, to understand whether specific-letter or non-letter processing is caused by early bottom-up processes of visual perception or by a later cognitive information processing, most studies considered intrinsic stimulus characteristics as well as context and task sensitivity.

The context-sensitivity is particularly important, because in reading, single letters are always contextually embedded.

The distinction between letters and non-letters as well as the formerly announced task specificity of congruency effects, is demonstrated by van Leeuwen and Lachmann (2004). In a binary classification task, they presented letters and non-letters (rotated letters, pseudo-letters and geometrical shapes) either in isolation or surrounded by a geometrical shape. This surrounding shape was either *congruent*, i.e. similar in their geometrical properties to the targets, or *incongruent*, i.e. different in their geometrical properties. The results of van Leeuwen and Lachmann (2004) suggested, that the occurrence of negative or positive congruency effects as well as the distinction between letters and non-letters depended on the task. If participants were explicitly or implicitly advised to make a *categorical classification* (i.e., they had to decide whether a target was a letter or a non-letter), negative congruency effects for letters but positive congruency effects for non-letters were observed. In contrast, when participants had to make classifications based on geometrical features (e.g., C and circle vs. H and square) both stimulus types showed positive congruency effect. This crucial instruction-dependent congruency effects can neither be explained by lateral masking, involving feature interaction and target selection, nor by simple attentional factors, causing response competition.

For non-letters, the congruent surrounded shapes were identified as fast as the isolated ones, which speaks against the basic assumption of lateral masking, in which a congruent surrounding should interfere with target detection. In principle, attentional processes like target selection can explain this observation (Bavelier et al., 2000), since this approach predicts that congruency effects vanish for simple shapes, whereas more complex stimuli, like letters, should show a negative congruency effect. Indeed, this effect was observed for letters, however, they were processed faster than the simple shapes, which cannot be explained with target selection difficulties. Hence, van Leeuwen and Lachmann (2004) used a feature integration approach (see van Leeuwen & Bakker, 1995) to explain their results. They assumed different perceptual integration strategies for shapes and letters.

For single letter detection it is important to ignore contextual features. This active suppression of surroundings leads to a negative congruency effect for letters. In contrast, for object recognition in general, it is more important to integrate con-

textual features. Therefore, shape recognition benefits from similar surroundings and shows a positive congruency effect. Since the categorial classification task promoted these different strategies, this explains the observed distinction between letters and non-letters. In contrast, if classification was explicitly based on visual features, more object recognition based strategies were promoted. Hence, letters as well as non-letter shapes showed positive congruency effects.

Those findings were further investigated by Lachmann and van Leeuwen (2004), using a same-different task instead of classification, to examine differences between letters and non-letters. In this study participants had to decide whether or not two successively presented stimuli (either letters or non-letters) were the same, while ignoring the surrounding. Thereby, the first stimulus was presented in isolation followed by a second stimulus, which was either presented in isolation, congruent surrounded or incongruent surrounded. Participants were divided into two groups. In one group, the *different* pairs were always distinct in their geometrical properties (e.g., an A and a circle), resulting in a positive congruency effect. In the other group, *different* pairs were similar in their geometrical properties (e.g., an A and a triangle), resulting in a negative congruency effect. This reflects a stronger response conflict for the similar pairs. In a second experiment similar and dissimilar stimuli were mixed. Since the same responses include either pairs of letters or pairs of non-letters, participants could also use an implicit letter vs. non-letter categorial distinction to differentiate between same and different stimuli. The results were in accordance to the assumption of different processing strategies for letters and non-letters. Whereas non-letter pairs showed positive congruency effects, these effects vanished for letters. To exclude the possibility of an implicit letter vs. non-letter categorial strategy, in Experiment 3, participants were explicitly advised to use a visual strategy. Same-responses included physical identical letters and non-letters as well as letters and non-letters, which were similar in their geometrical properties. This explicit instruction of an object recognition strategy leads to a disappearance of negative congruency effects, in accordance to the results of the prior described study of van Leeuwen and Lachmann (2004).

To summarize, both studies gave evidence for a distinction in congruency effects between letters and non-letter shapes, which could be explained by different

processing strategies. The usage of these strategies depends on the given instruction and the possibility to use an implicit or explicit differentiation between letters and non-letters to solve the task. Although the results showed that the congruency effects were not just caused by simple perceptual processes, it is not clear in which stage of information processing the context integration occurred.

Lachmann and van Leeuwen (2008a) examined this question by varying the inter stimulus interval (ISI) between the first and second stimulus in same-different tasks. In this paradigm, a letter was always followed by an isolated or surrounded letter and a non-letter was followed by an isolated or surrounded non-letter. They demonstrated that congruency effects for letters vanished for short ISIs, indicating an automatized letter processing strategy which is integrated in early visual processing. Therefore, with larger ISI the influence of this strategy is eliminated. Since, for fast letter processing there was no congruency effect, Lachmann and van Leeuwen (2008a) predicted a more *analytic letter processing strategy*, which is less context sensitive. In contrast, for non-letters a more *holistic processing strategy* is preferred, which results in a higher integration of the surrounding context.

Assuming different strategies predicts, that the distinction of congruency effects between letters and non-letters depends on the stage of reading development and the degree of reading expertise (Fernandes et al., 2014; Lachmann & van Leeuwen, 2008b). However, this prediction needs some further explanation. Fernandes et al. (2014) used a same-different task with surrounded letters and pseudo-letters to examine, whether developmental dyslexia is a result of anomalous letter processing. They divided participants into six groups: children diagnosed with phonological dyslexia, an age matched group with normal reading skills and a group matched for reading level as well as unschooled illiterates, ex-illiterates and schooled literates. For non-letters they found a congruency effect for all groups. For letters the dyslexics showed a congruency effect, which was strongly related to their phonological recoding abilities, whereas for children with normal reading skills the effect vanished. More remarkable results were observed for illiterate adults: they showed no overall congruency effect for letters. However, the congruency effect decreased with increasing letter knowledge and resulted in an absence of congruency effects for schooled literates. If reading expertise alone is the crucial factor of the distinction between letters and non-letters, the same pattern of res-

ults would be expected for illiterates as for dyslexic children. Hence, the results of Fernandes et al. (2014) seem to contradict this assumption, while showing that the congruency effect cannot simply reflect low-level visual familiarity. The authors suggested that the appearance of letter specific processing strategies is related to the stage of phonological awareness. Thus, adult illiterates possibly benefit from a stronger phonological awareness compared to the phonologically impaired dyslexics, even if the illiterates letter expertise is much poorer. That means, that the analytical letter specific processing strategies are not only activated by letter knowledge or familiarity but rather by a cross-model decoding of letters. This is in accordance with earlier results of Lachmann and van Leeuwen (2008b), showing that these letter-processing strategies even differ in diagnostic subgroups of developmental dyslexia. In the diagnostic differentiation of these subgroups phonological awareness plays an important role.

To summarize, congruency effects are caused by different stages of visual information processing, depending on the task and the visual features of the stimuli. Simple bottom-up processes are crucial for less complex visual shapes and tasks. Lateral masking can explain negative congruency effects, based on interaction of the local features of the presented objects (Estes, 1982). For more complex stimuli cognitive processes play an important role. Attention to the target and thus the need to suppress attention to the distractor leads to a negative congruency effect for more complex stimuli and a positive congruency effect for less complex stimuli (Lavie, 1995; Ruckl et al., 1991; Sanders & Lamers, 2002; Treisman & Gelade, 1980). Depending on the nature of the target, feature integration explains, how different processing strategies are integrated in an early stage of visual processing (van Leeuwen & Bakker, 1995; van Leeuwen & Lachmann, 2004). This approach considers the context in which the presented stimuli normally occur, and assumes a transfer of these strategies to other tasks, like the ones using surrounded figures. The strategies used for non-letters are assumed to be more holistical, which means that non-letter shapes are perceived more superficially and sensitive for contextual features. For letters these strategies are described as more analytical, meaning that perceptual strategies for letters integrate more internal features in a bottom-up process and allow efficient recognition on a top-down level, leading

to less visual context sensitivity. Hence, depending whether these strategies are useful for the specific task, these different strategies lead to a distinction in congruency. The access to the letter specific strategies depends on the stage of reading expertise and underlies a cross-modal representation of letters (Fernandes et al., 2014; Lachmann & van Leeuwen, 2008b).

2.5. The Global Precedence Effect

As described in the previous chapter I explained that the analytical letter processing strategy results in a less context sensitivity for letters compared to non-letters. This seems to be in contrast to the well-known **Global Precedence Effect (GPE)**: "*forest before trees*", to use a common metaphor (Navon, 1977).

The GPE is observed in paradigms, using compound, hierarchical figures – known as *Navon figures*² (see Kimchi, 1992, for a review). These figures consist of a global structure, defined by the spatial relationship between identical local shapes. For example, a stimulus described by four triangles arranged in a square. The square is the global level ("forest"); the triangles are the local level ("trees"). These compound figures have the advantage that global and local levels can be independently varied: besides a square of triangles, there can be a triangle of squares, a square of squares, and a triangle of triangles (see Navon, 1981, 2003). Compound figures in which the global level forms the same shape as its local elements (e.g., a square of squares) is described as congruent (see Figure 2.5, left column). If the global and the local level show different shapes (e.g., a square of triangles) the compound figure is called incongruent (see Figure 2.5, right column). The task can involve identification, classification, or discrimination of a target either at the global or local level.

The GPE implies, first, that for the global level target responses are faster than for the local level ones (*global advantage* or *global superiority effect*). The second observation pertaining to the GPE is called *asymmetric congruence*, i.e., incongruency interferes with the local-level target responses but not with global level ones.

²Although those figures were used by Kinchla (1974) first, later on they become popular as so-called Navon figures (Navon, 1977)

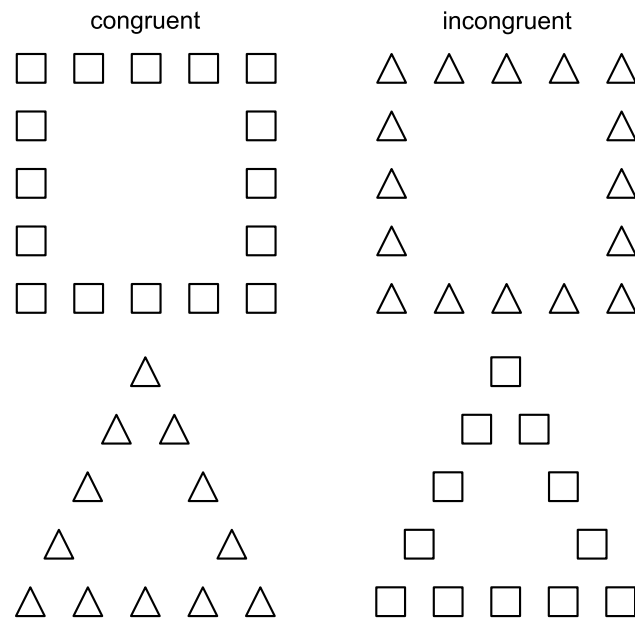


Figure 2.5.: Example of hierarchical compound figures (Navon figures). They are either congruent (left column) or incongruent (right column).

The occurrence of a GPE leads to the conclusion that the global-level properties have a processing priority, compared to the local ones (we first see the forest, then the trees). We might call this type of processing holistic³. Since, the GPE is mostly observed with compound figures, consisting of letters on the local as well as the global level (Dulaney & Marks, 2007; Lux et al., 2004; Navon, 1977; see Kimchi, 1992, for a review), this seems to be in contradiction to the view that while non-letter shapes are typically processed holistically, letters are processed analytically. We would at least *prima facie* expect an observer in analytic mode not to give priority in processing to the properties of the global shape - this, even though the present task is not quite the same as reading.

However, there are reasons to expect analytic processing leading to the disappearance of the GPE under particular circumstances. In spite of its abiding presence in the literature, the GPE is modulated by a variety of factors. Hence, the following sections will give a review about the findings of prior studies, consid-

³The dimensions local-global and analytic-holistic do not necessarily refer to the same construct (Wagemans et al., 2012)

ering the persistence of GPE in letters and non-letters and evidences for different processing strategies.

2.5.1. GPE and the law of closure

Since the global structure only exists because of the particular arrangement of the local level elements, we assume that these Navon figures are sensitive to those laws which we know from the *Gestaltgesetze: The whole is more than the sum of its parts*. In particular, the *law of closure* seems to have an influence on the appearance of the GPE. Martin (1979) demonstrated that with increasing space the global advantage shifted towards a local advantage. Similar results were found for the number of local targets. In a similarity judgement task, Kimchi and Palmer (1982) showed that in compound *non-letter figures*, in which the global structure was composed of a few local elements, those elements are perceived more as individual parts, that means, the global level is less dominant. With increasing number of local elements the global dominance increased, meaning the local elements were not perceived as single shapes anymore, but rather as part of the texture forming the global shape. The influence of size properties and spacing between the local elements depends on the geometrical properties of the shapes. Navon and Norman (1983) demonstrated that the GPE was more robust for shapes with smooth edges (e.g., squares), compared to shapes with serrated edges (e.g., triangles). However, Kimchi (1988) demonstrated that the asymmetric interference, for stimuli which differ at the global and the local level, was higher with increasing number of local elements, independently from the geometrical properties. These contradictory findings indicate that there seems to be no consistency in the influence of spatial features and number of local elements.

2.5.2. GPE and spatial frequency

LaGasse (1993) concluded, that not only the complexity of the figure but also spatial frequency influences the appearance and strength of the GPE. Her findings suggested that the global advantage in reaction times requires an unambiguous global form conveyed by low spatial frequencies. Assuming that the global level is processed more right-lateral, whereas the local level elements are processed more

left-lateral, Hübner (1997) investigated, whether this finding can be explained by different hemispherical processing capacities for spatial frequencies. However, he concluded, that also attentional mechanisms are responsible for the global advantage.

2.5.3. GPE and target placement

Navon (1977) discovered the GPE with spatial uncertainty in peripheral vision. Since then, a number of studies investigated presentation of compound figures away from fixation, in combination with positional uncertainty (e.g., Dulaney & Marks, 2007; Lux et al., 2004; Pomerantz, 1983; Volberg & Hübner, 2004), as well as in central presentation (e.g., Grice, Canham & Boroughs, 1983; Kinchla & Wolfe, 1979; Poirel, Pineau & Mellet, 2008). The variety of studies showed, that the GPE occurred for all presentation conditions, however, particularly for letters the results were often inconsistent and even contradictory. Therefore, in the following section I will compare some studies, separately for letters and non-letters.

Non-Letters. Although Navon (1977) primarily discovered the GPE under spatial uncertainty, in a follow-up study he used a central presentation not only to show that the effects also occur for central presentation, but moreover to show that the global advantage is even independent from the stimuli size (Navon & Norman, 1983). The influence of spatial uncertainty was systematically examined in Kimchi (1988). Her results suggested, that for non-letters the GPE could also be detected, if the stimuli were presented on a fixed peripheral position. Additionally, Kimchi and Merhav (1991) observed, that the appearance of global advantage for fixed peripheral presentation depended on visual hemifields. For the right visual field there was a local advantage, whereas the global advantage was observed for the left visual field. They explained this observation with different hemispherical sensitivity. Hence, the local elements should be processed more left-lateral and the global level more in the right hemisphere. Amirchiabani (1998) figured out, that the visual hemifield and consequently the hemispherical activation also affect the interaction between global and local level. The interference from the global to the local level was stronger when the stimuli were presented on the right side of fixation (i.e., left hemisphere), whereas the interference from local to global was stronger

in the left visual field (i.e., right hemisphere). This hemispherical distinction of global-local processing could also be underlined by other EEG studies (e.g., Gable, Poole & Cook, 2013; Volberg & Hübner, 2004, 2007). For *mixed stimuli* (i.e., global non-letters build-up of local letters or vice versa) the GPE was also observed for fixed central presentation as well as for spatial uncertainty. Martin (1979) observed global advantage under central presentation for global letters build-up of geometrical shapes. Dulaney and Marks (2007) presented mixed stimuli randomly $.76^\circ$ above, below, or on either side of the fixation point. The GPE was observed for each kind of stimuli.

Letters. Whereas the GPE for non-letters was quite robust for central presentation, for fixed peripheral presentation and even for spatial uncertainty, for letters, however, the effects were often found to be unstable, reduced, absent or sometimes even reversed (e.g., Ahmed & Fockert, 2012; Amirkhiabani & Lovegrove, 1996; Kinchla & Wolfe, 1979; Lamb & Robertson, 1988, 1990; Pomerantz, 1983).

Kinchla and Wolfe (1979) used a central presentation and showed that for letters the GPE depended on stimulus size. In contrast, there were also studies, suggesting a more local advantage for centrally presented letter stimuli (e.g., Grice et al., 1983; Pomerantz, 1983). Pomerantz (1983) investigated central vs. peripheral presentation. Stimuli were presented within the foveal focus in the center of the screen or 3° from the center of the screen, so that they fall outside of the foveal focus. The global advantage was observed for peripheral but not for central presentation. Thus, they proposed that local elements are benefited in central presentation, because they fall into the foveal field of view. Therefore, for central presentation the global advantage is reversed to a local advantage. In turn, the distance from the fovea in peripheral presentation affects the local letters more than the global letters, leading to a superiority of the global level. Using a peripheral presentation 2.47° from the fixation point, Grice et al. (1983) came to the same result and proposed, that the GPE depends on factors tending to degrade small stimuli more than large ones. Lamb and Robertson (1988) tried to answer the question, whether the spatial uncertainty affects the local and the global level in different ways. If a foveal presentation benefits the local level elements, then the same advantage in reaction time should be observed for single letters with the same size as those local elements. Their results showed indeed, that the local elements

of the compound figures were identified faster when they were presented centrally, however, the decrease in reaction times for central compared to peripheral presentation was not observed for the single letters, which were not embedded in a hierarchical structure. This distinction between embedded and single letters vanished when the stimuli were always presented centrally.

2.5.4. GPE and stimulus size

During the last decades the GPE was observed in many studies, using different visual angles (see Kimchi, 1992). Some of those studies examined systematically the influence of absolute stimulus size and eccentricity from the focal point of view. Whereas for non-letters effects appear relatively invariant, for letters effects crucially depend on the visual angle of the global target. This dependency was consistently observed across a number of studies (e.g., Ahmed & Fockert, 2012; Amirkhiabani & Lovegrove, 1996; Kinchla & Wolfe, 1979; Lamb & Robertson, 1988, 1990; Luna, Marcos-ruiz & Merino, 1995; Navon & Norman, 1983; Pomerantz, 1983).

Non-letters. The GPE for non-letter stimuli occurred under different visual angles (e.g., Bouvet, Rousset, Valdois & Donnadieu, 2011; Davidoff, Fonteneau & Fagot, 2008; Harrison & Stiles, 2009; Hughes, Layton, Baird & Lester, 1984; Kimchi, Amishav & Sulitzeanu-Kenan, 2009; Kimchi & Palmer, 1982; LaGasse, 1993; Luna, Merino & Marcos-Ruiz, 1990; Navon, 1977; Navon & Norman, 1983; Peressotti, Rumiati, Nicoletti & Job, 1991), thus, the effects are quite robust, independently from the stimulus size. For non-letter stimuli, the influence of stimuli eccentricity to the GPE was explored by Navon and Norman (1983). Their stimuli were composed of closed circles and circles with a small gap, either left or right, and were presented under visual angles of either 2° or 17.25° . Participants had to decide, whether the opening of the circles was on the left or on the right. Their results showed a global advantage for both visual angles, suggesting that for those kind of stimuli the global advantage is persistent even for large visual angles.

Letters. Kinchla and Wolfe (1979) investigated, whether the global or the local level of compound figures would be processed first, depending on the absolute stimulus size. For compound letters they varied the visual angle and participants

were asked to respond as soon as they detect a pre-designated target, independently on which level the target was presented. By varying the visual angles within a range of 4.8° and 22.1° , they found, that for smaller visual angles the global level was processed faster than the local one, whereas for larger visual angles the local elements were detected faster than the global ones. These results suggested, that the global advantage for letters reverses from a visual angle of about $6-9^\circ$ upward. They concluded that the perceptual system is sensitive for stimuli, which appear under a *crucial visual angle*, and therefore stimuli, falling within this perceptual threshold are preferred, compared to stimuli which appeared under a larger or smaller visual angle.

Amirkhiabani and Lovegrove (1996) found the GPE to disappear with a visual angle of global letters between 2.5° and 4.6° . Lamb and Robertson (1990) varied the visual angles from 1.5° to 12° and found that the global advantage effect for letters is restricted to visual angles smaller than 4.5° . Luna et al. (1995) presented the global letters with visual angles of 3° , 6° , and 12° and found, in agreement with the previous studies, the GPE with letters to be restricted to the small visual angle condition of 3° . With 6° the GPE disappeared and in the 12° condition it is reversed. These results make it likely that central presentation of global stimuli between 5° and 6° approximately in size leads to a differentiation between letters and non-letters in their GPE effect.

2.5.5. GPE, target detectability and attentional bias

Navon (1981) claimed:

”It seems to me that the effect of global precedence is probably due to several mechanisms. I believe that some of them are sensory and some others are cognitive. I venture to guess that Nature would not have let a functionally important property of perceptual processing (see Navon, 1977, pp. 355–356) hinge on the satisfaction of just one antecedent condition. Regardless of how valid this position is, the dependence of global precedence on each of its conceivable mediating mechanisms is yet to be determined.”(Navon, 1981, p. 21)

Since the previously mentioned conditions (i.e., spatial frequency, target placement, size of the targets) influence the detectability of the target levels, we could assume that the discriminability of the targets is a crucial factor to the appearance of the GPE.

Pomerantz (1983) claimed, that the global advantage and the interference to the local level is caused by differences in discriminability between the global and the local level instead of an overall superiority of the global level. With increasing perceptual quality of the local level, therefore, the effect can be reversed. Kimchi (1992) rejected in her review this strong assumption by referring to a number of studies that demonstrated the GPE in various contexts under different conditions. According to Kimchi (1992, p. 29) "evoking discriminability per se as an account of global advantage is hardly tenable". However, she admitted that the conditions which influence the discriminability have to be controlled to predict a predisposition of the perceptual system for the global level. In accordance with Hübner (1997), she came to the conclusion, that the GPE is not just observed in most studies, because of a better detectability, but that attentional mechanisms play an important role in the appearance of GPE. The role of a more abstract attentional bias was subject in a study of Förster and Higgins (2005). Before their global-local task, they measured the strength of individual *promotion focus* (i.e., ideals: hopes or aspirations, concerns with accomplishment) and *prevention focus* (i.e., oughts: duties or obligations, concerns with security), based on preliminary work by Higgins, Shah and Friedman (1997). Results showed, that the speed of processing the global level was positiv correlated with a promotion focus, whereas the processing speed of the local level showed a negative correlation. For the strength of prevention focus, the directions of correlations were reversed. Although the study was focused on emotions and self-concept aspects, which is related to a higher, more complex cognitive bias, their results seem to support the idea, that the GPE is not just caused by perception but also by even higher cognitive processes. In a more directly visual context Poirel, Pineau, Jobard and Mellet (2008) demonstrated, that the GPE depends on field-dependency characteristics. The bias toward the global level (measured with a Group Embedded Figure test) was linearly related to the degree of field dependence, suggesting that visual skills as well as attentional biases play an important role in the appearance of GPE.

Later, they showed that the bias to global or local processing depends also on the stage of brain development (Poirel, Leroux, Pineau, Houdé & Simon, 2014). A decrease of cortical thickness in the bilateral occipital regions together with an increase of cortical thickness in the left frontoparietal regions leads to an increase of global perception.

To summarize, target detectability alone cannot explain the findings in the context of compound figures, rather there seems to be an interaction between sensory and cognitive mechanisms, which leads us back to the quote of Navon (1981) at the beginning of this section.

2.5.6. GPE and the categorical nature of stimuli

Considering the idea of underlying cognitive processes, Poirel, Pineau and Mellet (2006) went another way to explain the superiority of global level and the interference occurring in Navon paradigms. They used compound figures composed of nameable objects (e.g., pictograms of animals) and non-objects (i.e., random scribbles). When the target level showed objects, they observed the classical GPE, independently from the identity of the shapes at the irrelevant level. However, when the relevant level showed non-objects and the irrelevant level included objects, the GPE was reversed. They assumed a parallel processing of an automatic identification and structural analysis, which is responsible for the appearance of GPE. In a later study they transferred this finding to letter stimuli. Whereas most researchers used either letters or non-letters while investigating the effect of various factors on the GPE, Poirel, Pineau and Mellet (2008) examined the difference between letter *and* non-letter material, however, without systematically comparing letters and non-letters under different presentation conditions. They used compound figures based on either meaningful stimuli, i.e. letters and pictograms of real objects (e.g., umbrellas or flowers) and meaningless random scribbles, to examine how the GPE is affected by the meaningfulness or lexical content of the stimuli. Their results suggest, that the global advantage was independent from the material, however, the interference effect occurred only with meaningful stimuli. Poirel, Pineau and Mellet (2008) interpreted these results, as evidences that the global advantage is caused by *sensory mechanisms*, whereas *cognitive mechan-*

isms, are responsible for the asymmetric interference effect. This interpretation is in accordance with Boucart and Humphreys (1992), who demonstrated that object identification is a crucial factor in global shape perception. The results of Poirel, Pineau and Mellet (2008) could be replicated in a follow-up ERP study (Beaucousin et al., 2011), showing differences in the P1 and N1 between non-objects on the one hand, and letters and nameable objects on the other hand. Hence, looking for meaning seems to be crucial in the perception of visual scenes, particularly in the context of global and local perception.

However, we assume that meaning alone cannot explain the distinction in GPE for different kinds of stimuli. The influence of meaningfulness rather must be modulated by an underlying distinction in cognitive processes, which in turn are modulated or triggered in a cross-modal mode by presence or absence of lexical or phonological content.

2.5.7. Letter vs. non-letter distinction in GPE

There is still the main question, whether there are evidences for different processing strategies between letters and non-letters in global-local tasks.

In the previous sections I discussed, that the GPE is modulated by a variety of factors, including internal factors such as the number of components (e.g., Kimchi & Palmer, 1982; Navon & Norman, 1983), detectability of the local and global features (e.g., Kimchi, 1992), the visual hemifield (e.g., Amirkhiabani, 1998) and spatial frequency characteristics (e.g., Hübner, 1997; LaGasse, 1993). Particularly, the mode of presentation seems to give evidence for a distinction in processing of letters and non-letters. This includes the absolute and relative size, more exactly, the visual angle under which the global and the local level appears (e.g., Amirkhiabani, 1998; Amirkhiabani & Lovegrove, 1996; Kinchla & Wolfe, 1979; Lamb & Robertson, 1990; Luna et al., 1995; Martin, 1979; Navon & Norman, 1983; Pomerantz, 1983) and the target placement: whether the target is presented foveally or peripherally combined with positional uncertainty (e.g., Kimchi, 1988; Kimchi & Merhav, 1991; Lamb & Robertson, 1988; Navon, 1977; Pomerantz, 1983).

This distinction between *target size* and *placement* is in accordance with prior studies, which examined requirements for letter processing in other contexts. For

letter specific analytic processing, it appears crucial that the targets are presented in *central view*, without positional uncertainty (Plomp, van Leeuwen & Ioannides, 2010). The reason may be that reading typically occurs in a piecemeal fashion, while the sensory information is close to the locus of fixation (Rayner, Balota & Pollatsek, 1986); parafoveal vision in order to control saccades may be important for reading, but uptake of orthographic information takes place only within central vision (Jordan & Martin, 1987; Pollatsek, 1993; Rayner et al., 1986; Stein, 2002; Stein et al., 2001). If analytic processing of letters is due to reading expertise, it is more likely to be found in conditions where the target is placed centrally in visual field.

Apart from the central presentation, a specific *size ratio* of the global and the local level seems to be crucial for the appearance of reading specific processing. For the size of the local level there is a critical threshold for fluent reading in central vision, which is approximately 0.3° of visual angle (Jordan & Martin, 1987; Legge, Pelli, Rubin & Schleske, 1985). Reading becomes less fluent with larger stimuli. For the global level the whole structure of compound figures appears within the functional visual field (approximately $5 - 10^\circ$ of visual angle around the fixation point), in which an object as well as its component parts can be seen (Sanders, 1970). This means that the local (letter) and global level can be processed in parallel. For fluent reading it seems to be crucial that the word-level information needs to be captured within a restricted area.

Therefore, we propose that the observed distinction between letters and non-letters is caused by the specific conditions, in which effects of analytic processing in letters are most likely to be found, i.e. central presentation and a size ratio, which is typical for fluent reading. In contrast, non-letters are still processed holistically under these conditions, suggesting that the GPE for non-letters is more robust independently from the chosen conditions. However, since for this type of conditions, no comparison between letters and non-letters has been made so far, this conclusion would be based on indirect evidence.

The few studies which compared letters and non-letters used either peripheral presentation (e.g., Dulaney & Marks, 2007; Martin, 1979) or, if they used central presentation, did not vary the material systematically (e.g., Peressotti et al., 1991, only varied material at the global level) and if they did, they used rather large

visual angles for the global level (e.g., Beaucousin et al., 2011; Poirel, Pineau & Mellet, 2008). Hence, the assumption, that the difference in GPE for letters and non-letters results from different processing strategies, is still based on the comparison of the previous studies and needs to be subject of further studies.

2.6. Serial-position effects in letter and non-letter strings

The dual-route models of reading distinguish two different routes which are essential for fluent reading: a lexical route, in which the pronunciation of a whole word is retrieved from a mental dictionary, and a non-lexical route, which requires a sequential grapheme-to-phoneme decoding (see Chapter 2.2.2). The distinction was confirmed in many studies (e.g., Coltheart et al., 1993, 2001; Forster & Chambers, 1973; McCann & Besner, 1987; New et al., 2006; Paap & Noel, 1991; Rastle & Coltheart, 1999b; Seidenberg et al., 1984; Taraban & McClelland, 1987).

According to the assumptions of a dual route model, on the one hand, we expect to find a more serial perceptual process (caused by the non-lexical route), showing a linear trend from left-to-right (e.g., for German, English, French) or right-to-left (e.g., for Arabic, Hebrew), respectively, with respect to the typical rules of orthography. On the other hand, the idea of a lexical route is based on the identification of cue letters, which activate information from long-term memory. Hence, this route should be sensitive to specific letters or multi-letter units and their position in a word. Since, the lexical route benefits from lexical and semantic content, whereas the non-lexical route does not, especially for skilled readers the lexical route plays a dominant role. For non-words this dominance is suppressed, however, as assumed by the "hose-and-bucket model" (see Chapter 2.2.2), both routes are still active, which allows to examine both underlying processes equally.

Without considering those two routes, Haber and Standing (1969) demonstrated that in a letter string the central and terminal positions were detected more accurately, than the neighboring positions, resulting in a *W-shaped position function* for accuracy (or *M-shaped* for error rates). For reaction times similar pattern of results were found by Mason (1975). In five-letter strings target let-

ters were detected faster at the initial, central and final positions of the string (*M-shaped position function*) joint with an increase of reaction times from left to right (*linear serial position effect*). Additionally, she found that *spatial frequency redundancy* and *sequential redundancy* influenced the speed of letter detection. *Spatial frequency redundancy* means how frequently a specific letter is at a specific position in written real words (e.g., the letter "y" is highly frequent at the end of English printed words). *Sequential redundancy* considers the sequential order of specific letters in typical multi-letter units (e.g., the letter "l" often precedes the letter "y"). The results of Haber and Standing (1969) and Mason (1975), seem to support the idea of different reading routes. The left-to-right trend reflects the sequential encoding, which is typical for reading English (Bryden, 1967; Heron, 1957; Mewhort, 1974) and caused by the non-lexical route. The advantage of the terminal positions and the consideration of typical letter-position correlations can be ascribed to the cue-reading based lexical route. Though, these letter strings were often used to examine visual processes (e.g., Haber & Standing, 1969; Sperling, 1960). There was an extensive debate whether these findings are due to *sensory* or *cognitive mechanisms*. Supporters of the *sensory perspective* explained the left-to-right trend by post-perceptual mnemonic organization (Harcum, 1967) and a response bias to the left side of the strings (Ayres, 1966). The advantage of the central position was explained by a benefit from foveal perception of the center letter, where visual acuity is greatest (Mason, 1982; Wagstaffe, Pitchford & Ledgeway, 2005). Following this explanation of a decrease of acuity with eccentricity the benefit for terminal positions is contra-intuitive. However, this could be explained in terms of lateral masking effects (Estes, 1972; Haber & Standing, 1969), since the terminal positions are less inhibited by flankers.

If these findings of an M-shaped position function for reaction times and error rates resulted just from *sensory mechanisms*, there should be the same pattern of results for strings composed of non-letter material. Mason and Katz (1976) conducted a similar experiment, but with a Greek letter set instead of the formerly used Latin letters. Their results showed again a preference for the central position, however, the terminal advantage vanished. For the Greek letters, which were non-letters from the participant's point of view, the pattern of results showed a more U-shape positional function with fastest responses for the central position and in-

creasing reaction times to the terminal positions. Although this speaks against the sensory explanations for the elevated end-effect, Mason and Katz (1976) proposed that the observed differences to their prior study were due to differences in luminance and string size (six instead of five characters). Inspired by this contradiction, Hammond and Green (1982) compared systematically letters and non-letters in five-character strings. They came to the result, that even under the same conditions letters and non-letters differ in the appearance of end-effects. Letters remained the *M-shaped function* and an overall *linear increase form left to right* in RTs, whereas non-letters showed a *U-shaped function* with a symmetrical increase in RTs from the central to the terminal positions. Furthermore, comparing different letter and non-letter sets, they demonstrated that this distinction is not due to visual complexity, nameability or familiarity. They interpreted their results as evidence that the *letter position function* is caused by *cognitive processes* and not by *sensory mechanisms*. In the same year, Mason (1982) published a study, which compared letter, non-letter and in addition digit strings. Apart from a replication of Hammond and Green (1982) the digit strings also showed a serial position function with increasing RTs from left to right. Although the fifth position of digit-strings showed a slight decrease in RTs, the terminal position advantage was more restricted to the first position. The central position showed no advantage. This reflects that the serial position function is not limited to letters, however, the pattern of results are slightly different. In the same study she demonstrated that the letter vs. non-letter distinction was independent from retinal placement (foveal vs. parafoveal presentation) and array size (three- vs. five-character string). She contradicted her formerly interpretation and conceded "that sensory factors cannot provide a viable account of letter end-effects and that letter and non-letter comparison can improve our understanding of sensory and cognitive factors involved in letter perception" (Mason, 1982, p. 724).

Whereas end-effects in letter-strings can be ascribed to cognitive processes, which reflect the reading strategy of the lexical route, the observed linear left-to-right increase results from the serial encoding of written words, typical for the English writing system, in which words are written from left to right. Hence, an increase from right to left for other writing systems like Hebrew or Arabic would be expected. Farid and Grainger (1996) tested this idea by comparing French and

Arabic readers. Whereas French readers showed the expected overall left-to-right trend, in Arabic readers no asymmetry in the serial position function was observed. Since Arabic readers showed no trend, simple orthographic constraints could not be a sufficient explanation of the formerly observed linear trend. However, sensory explanation caused by hemispheric asymmetry also fails to explain these results. Farid and Grainger (1996) interpreted their results in terms of lexical constraints instead of orthographic or sensory ones. Statistically significant, in French or English the first letter of a word is more important to require the lexical content. For example, the word FABLE can get easily guessed, if the first four letters are presented (FABL_). Omission of the first letter (_ABLE) is less informative since a lot of words are possible (e.g., CABLE, TABLE; Farid & Grainger, 1996). Hence, while reading French (the same hold true for English and German) there is an attentional bias towards the beginning of a word. This is reinforced by the fact that in complex words the morphological roots at the beginning of the word involve more lexical information than suffixes at the end of a word, mostly just reflecting grammatical constraints (i.e., conjugation and declination). In contrast, the Arabic consonantal scripture and non-concatenative morphology⁴, gives the notion of roots an important role in linguistic processing (Farid & Grainger, 1996). Hence, the beginning and ending of written words matter equally, what explains the lack of an linear trend in any direction for Arabic readers. Lexical constraints seem to be more important than orthographic constraints, reflecting the dominance of the lexical route in a less transparent orthography like Arabic.

In turn, we expect a preference for the non-lexical route for more transparent orthographies like German or Greek. Ktori and Pitchford (2009) demonstrated this prediction by comparing reading beginners of English or Greek orthography. The English as well as the Greek readers showed an advantage for the initial and central position, however, the final-letter facilitation was only observed for English readers. For Greek readers the linear left-to-right trend was more pronounced, showing that the non-lexical serial decoding strategy is more dominant for readers of transparent orthography, than for readers of intransparent orthographies. Thus,

⁴Non-concatenative morphology means that words are declined or conjugated by changing the morphological root (e.g, **foot** → **feet**) instead of adding prefixes or suffixes (e.g., **game** → **games**). In English, German or French most words are inflected following straight grammatical constraints.

the letter position encoding is adaptive to the nature of the orthography acquired during reading development (Ktori & Pitchford, 2009).

Since the sensory mechanisms are similar to those, which were described for flankers and Navon figures, we expect that the observed effects also vary with the task. The M-shaped functions for reaction times and error rates were mostly observed in visual search tasks, in which participants had to detect a pre-designated target in a character string or in full report tasks, in which participants had to report the complete letter string (Hammond & Green, 1982; Ktori & Pitchford, 2008, 2009; Mason, 1975, 1982; Mason & Katz, 1976; Pitchford, Ledgeway & Masterson, 2008). Tydgat and Grainger (2009) used a two-alternative forced choice (2AFC) task in which the stimuli string was followed by a mask (a string of hash keys, #####). The two alternatives were displayed above and below a specific position of the hash key string and the participants had to decide which of these alternatives was present at this position of the pre-designated character string. In this 2AFC task the advantage at position five vanished, which was explained by interference from the alternative letters at this specific position (Tydgat & Grainger, 2009). However, they gave no explanation why the linear trend also vanished for this kind of task.

Furthermore, Tydgat and Grainger (2009) examined whether the distinction between letters and non-letters also holds for mixed stimuli in which a target letter was presented in a string of symbols or vice versa. The results suggested that the typical letter and non-letter position functions also appeared in mixed stimuli, depending on the target. Driven from this result, Grainger, Tydgat and Issele (2010) yielded an alternative approach, which integrated the *sensory mechanisms* and *cognitive processes* in the context of *crowding*. They predicted a distinction of *crowding space* between letters and non-letters. To test this hypothesis, they presented letters or symbols peripherally, flanked by either one or two items of the same category. The flanker interference was significantly larger for symbols compared to letters. By varying the space between target and flankers, they demonstrated that also the critical space, in which flankers interfere with the target, was larger for symbols than for letters. Hence, Grainger et al. (2010) proposed a specialized system, originally developed for reading, which determines crowding space. This reduction of the receptive field for letters is a result of reading acquisition to

enable parallel processing of letters in words (Stevens & Grainger, 2003).

Lateral masking can explain the facilitation of terminal positions in letter strings, but not the disappearance of this effect in non-letter strings; the *crowding hypothesis* can explain both. Whereas for non-letters even a single flanker interferes with the target, the shrunken receptive field for letters leads to a decrease of interference and thereby to a facilitation of the terminal positions, where letters are only flanked by one distractor, compared to the inner positions where they are flanked by at least two distractors. It should be noted, that the assumption of different crowding areas can, indeed, explain the end-effects, but neither the linear trend nor the letter-frequency effects. However, the idea that letters are processed in a restricted area is very similar to the assumption of an analytical letter specific processing strategy, which is biased to the internal features of letters.

To summarize, the previously described studies demonstrated that the processing of letter strings differs to that of non-letter strings. This suggests, that the predicted letter specific processing strategies are not limited to single letters but influences the letter perception in strings of letters. For *non-letter strings*, the pattern of responses reveal a quadratic *U-shaped function* for reaction times and error rates, and was explained by sensory mechanisms involving a centre-out scanning (Hammond & Green, 1982; Pitchford et al., 2008), especially if the stimuli were presented centrally. The quadratic term of the functions describes the decrease of visual acuity from the foveal to the parafoveal retinal field (Wagstaffe et al., 2005). For *letter strings*, this explanation only holds for the advantage at the central position. The facilitated end-effects reflect the influence of a lexical process, which is developed during reading acquisition to enable recognition of whole words. The influence of reading habits also explains the linear left-to-right trend for reaction times and error rates. Particularly, in transparent orthographies and in reading beginners this trend is in accordance to the serial decoding of letters in written words (Green et al., 1983; Hammond & Green, 1982; Ktori & Pitchford, 2008, 2009).

Although the studies in this context mostly used non-words or random letter strings, there are evidences that these results also could get transferred to perceptual and cognitive processes of real word reading. The DRC model assumes

different routes which predict similar processes as found for the previously mentioned studies. The importance to identify cue-letters (e.g., terminal and central letters in a word), which enable fast processing within the lexical route, is in accordance with eye-tracking studies in more natural contexts of reading (e.g., White, Johnson, Liversedge & Rayner, 2008). In turn, the fact, that spatial and sequential letter frequency in real words influences the reaction times at the same positions random letter-strings, demonstrated that in solving these tasks also orthographic processes are involved (e.g., Pitchford et al., 2008). Questions are, however, what determines the access to these strategies and at which stage of the perceptual process are these strategies involved; do they bias the perceptual process of object recognition or are they triggered by the stimulus itself?

3. Research questions

Specific letter processing has been observed in several paradigms using a large variety of different stimuli. However, it is still argued whether this specific letter processing is just caused by familiarity or nameability, allowing information retrieval from short- and long-term memory, or underlies some specific constraints, resulting from the development of letter- and reading-specific strategies.

Hence, the current thesis will try to find evidence for letter-specific processing strategies and thereby, to show that familiarity and nameability are not sufficient to explain prior findings. One crucial difference between familiarity and specific processing strategies is the influence of automatization. Most models of reading acquisition emphasize the role of automatization, especially the functional coordination model (FCM; see Lachmann & van Leeuwen, 2014). To enable fluent reading it is not sufficient to access earlier developed object recognition strategies. They have to be modified to develop reading strategies. Furthermore, these new reading-specific strategies have to be automatized. Thereby, the effectivity of automatization crucially depends on the specific context, in which the automatization occurs. In turn, familiarity is caused more by repetition than by context. Hence, if letter processing is restricted to specific constraints, this would underly the role of automatization, and thus, support the assumption of letter-specific processing strategies. Study 1 examines temporal and visual constraints of letter processing to exemplify the impact of specific conditions during reading acquisition.

The persistence of these strategies will be the question in Study 2. Reading acquisition usually requires a long time of extensive training. The neuronal recycling theory predicts that reading strategies result from recycling of earlier developed object-recognition strategies. Following this hypothesis, the time in which reading beginners become more advanced reflects the time in which the neuronal recycling occurs. Hence, for skilled readers it should be much easier to learn new

letters, i.e. to transfer the recycled strategies to new shapes. In contrast, the FCM emphasizes, that these strategies are not just a result of recycling, but rather a result of automatization, requiring a long-term procedural training. To compare these two approaches, in Study 2, participants have to learn new letters in a training. If pairwise graphemes-phoneme association is sufficient to trigger letter-specific processing strategies, this will support the neuronal recycling hypothesis, otherwise, the results again indicate the impact of automatization for developing proper letter processing strategies.

In turn, a lack of automatization has been suggested as one possible predictor of reading difficulties. Hence, Study 3 compares the difference of letter processing in children with normal reading skills and children with poor reading skills. Since the latter group is also familiar with the concept of letters as meaningful units, differences between the two groups can be described as differences in letter processing strategies instead of familiarity or nameability. A lack of typical letter-specific processing in children with poor reading skills, hence, indicates a lack of automatization during reading acquisition.

Since reading is based on decoding words, rather than decoding single graphemes to phonemes, this thesis also aims to expand prior findings for analytic letter processing to the context of whole word reading. In a random character string, letters should be processed in a serial left-to-right fashion as a result of automatized reading strategies, which are described in the dual-route model of reading. This would mean, that automatization is not only an essential part of letter representation but also plays an important role in later phases of reading acquisition, in which reading becomes more fluent.

4. Study 1: Congruency effects in letters and non-letter shapes

4.1. Aim of the study

Many studies demonstrated different effects for letters and non-letters, for example for symmetry (Fernandes & Kolinsky, 2013; Lachmann & van Leeuwen, 2007; Pegado et al., 2014, 2011) or congruency (Lachmann & van Leeuwen, 2004, 2008a; van Leeuwen & Lachmann, 2004; see Chapters 2.4, 2.5). These distinctions between letters and non-letters are explained by different processing strategies; a more *analytic processing strategy for letters* and a more *holistic object recognition strategy for non-letter shapes* (see Lachmann & van Leeuwen, 2014, for a review). However, alternative explanations for the observed letter versus non-letter distinction predicted a stronger influence of sensory mechanisms (Estes, 1972, 1982; Pomerantz, 1983). Using a cognitive or attentional approach, the role of familiarity or nameability (Beaucousin et al., 2011; Boucart & Humphreys, 1992; Navon, 1977; Poirel, Pineau & Mellet, 2008) was ascribed to be responsible for the distinction. The following experiments examine some specific constraints of letter processing, which underline the influence of automatization of letter processing, hence, indicating that letter processing is based on specific processing strategies instead of familiarity or nameability. This study also serves to find a paradigm, delivering reliable results, in order to conduct a training study (see Study 2) with a pre- and posttest. Therefore, we compared different sets of non-letters to minimize the influence of similarity effects.

4.2. Experiment 1: The time course of letter recognition and the role of automatization

In *Experiment 1*, we modified a paradigm, which is described in several studies, examining exactly these distinctions between letters and non-letters in contextual embedded figures (e.g., Fernandes et al., 2014; Lachmann & van Leeuwen, 2004, 2008a; van Leeuwen & Lachmann, 2004; described in more detail in Chapter 2.4). These paradigms use letters and pseudo-letters, which are surrounded by geometrical shapes (flanker), which either matches the geometrical properties of the surrounded character (e.g., an A surrounded by a triangle; congruent surrounding), or differ in their geometrical properties (e.g., an A surrounded by a circle; incongruent surrounding). Instead of pseudo-letters we used letters from the Hebrew and Cyrillic alphabet, which are very similar in their visual features to that of the Latin letters. Assuming that there is a universal letter-specific processing strategy for all graphemic writing systems, it is obvious that those letters in principle could be processed in the same way as Latin letters. For imaginary pseudo-letters this assumption is not that reliable. However, since our participants were not trained in these other alphabets, they should use the same processing strategies as for pseudo-letters, because these are not embedded in that set of letters which activates letter-specific processing strategies. Therefore, we expect the same distinction between Latin letters on the one hand, and Hebrew and Cyrillic letters on the other hand, as between Latin letters and pseudo-letters.

However, prior studies demonstrated that this paradigm is very task- and context-sensitive, meaning different effects were observed, depending on the specific instruction and presentation mode. Reliable letter versus non-letter distinction was found in tasks, which allow a categorical classification. When participants were explicitly advised to discriminate between letters and non-letters, negative congruency effects were observed for letters, meaning that incongruent surrounded letters were processed faster than congruent surrounded ones. Positive congruency effects were observed for non-letters, meaning that congruent surroundings benefit non-letter processing compared to incongruent surroundings. The same distinctions hold for tasks which allowed an implicit differentiation between letters and non-letters. In contrast, if this categorial classification was not necessary to solve

the task, the distinction in the observed effects was not that reliable. Lachmann and van Leeuwen (2008a) demonstrated that the effects for letters and non-letters crucially depended on the time course of letter recognition. In a same-different task participants had to decide whether or not two successively presented letters or non-letters are the same. The negative congruency effect for letters was only observed for short presentation times of the first stimulus and short inter-stimulus intervals (ISI) between the first and the second stimuli. Their results suggested that the highly automatized letter processing is effective if letters are presented at a relatively fast rate. This benefit gets eliminated for a slower rate of stimulus presentation.

Unfortunately, a categorial classification as well as a fast presentation rates, are not practicable for our purpose. Although, the participants in our training study should adopt shapes as new letters, we can neither expect that they quickly classify these shapes as letters in a classification task, nor that the processing of the new learned shapes is as automatized as for real letters. Hence, we had to find a compromise between explicit classification and fast presentation rate. To eliminate the influence of categorial classification we decided to use a same-different task as described by Lachmann and van Leeuwen (2008a). In their same-different task (no categorial classification) the negative congruency effect for letters appeared for an ISI of 320 ms and 1200 ms and disappeared for 2920 ms. We guessed that even after training the processing of the new learned "letters" is less automatized as for real letters, and thus, does not have an effect within the small ISI. Hence, we had to choose the largest ISI (1200 ms) under which the negative congruency effect was observed. To minimize the influence of different familiarity between letters and non-letters we also chose a larger presentation time for the first stimulus. We expected to find a distinction in congruency effects between letters and non-letters (i.e., Hebrew and Cyrillic letters) even for slightly larger ISIs and presentation times.

Hypothesis 1. *Hebrew and Cyrillic letters show congruency effects, whereas for Latin letters the congruency effect vanishes.*

However, there are strong evidences that our chosen conditions are too slight to observe a distinction, because the benefit of automatized processes plays a crucial role in this paradigm. It should be noted, that Lachmann and van Leeuwen (2008a) used the short ISI of 320 ms for an experimental design in which the non-letter targets were presented two times more often than the letter targets; the large ISI was used in a balanced 1:1 design. Since we used two unknown letter sets and only one familiar letter set this imbalance could lead to a preference for the holistically processing strategy. Hence, if no distinction between letters and non-letters is observed, the experiment extends prior findings by indicating that the appearance of a negative congruency effect depends not just on the given instruction and the temporal processing, but also on the experimental design.

4.2.1. Method

Participants

Forty-one students (22 female, $M_{age} = 24.2$ years, $SD_{age} = 3.4$ years) from the University of Kaiserslautern, Germany, participated in this study. All were right-handed German native speakers with normal or corrected to normal vision. They either were paid or received course credit for their participation. Participants signed consent forms prior to the study. The study was approved by the ethical committee of the Faculty of Social Science of the University of Kaiserslautern.

Material

Four capital letters from the Latin alphabet (**A, E, G, W**), four from the Hebrew alphabet (**א, ה, פ, ש**) and four from the Cyrillic alphabet (**Д, П, Э, Ш**) were used as stimuli. All letters were self-drawn and partially abstracted to match their visual features as closely as possible (Figure 4.1). These letters were presented in isolation or surrounded by one of four geometrical shapes, which were similar to the geometry of the letters (circle, triangle, square or trapezoid). Corresponding to their geometrical configuration the surroundings could be congruent to the letter (e.g., an A surrounded by a triangle) or incongruent (e.g., an A surrounded by a circle). In order to achieve a better experimental balance, from the three possible







	isolated	congruent	incongruent
Latin letters	A E G W		
Cyrillic letters	А П С Ш		
Hebrew letters	א ב ג ד		

Figure 4.1.: Illustration of the stimuli. Latin letters (upper line), Cyrillic letters (middle line) and Hebrew letters (bottom line) were presented isolated (left column), congruent surrounded (middle column) or incongruent surrounded (right column)

incongruent combinations for each letter only one combination was used, resulting in a total of 36 possible target stimuli (12 isolated, 12 congruent surrounded and 12 incongruent surrounded, see Figure 4.1). Stimuli were presented in black (0.4 cd/m^2) against a white background (28.9 cd/m^2). The experiment was conducted on a PC with Microsoft Windows 7 using E-Prime 2.0 (Psychology Software Tools, Pittsburg, USA), in a test cubicle with sound attenuation and controlled lighting.

Procedure

In a same-different task participants were asked to decide whether or not two successively presented letters were the same, while ignoring the possible surrounding. Instruction was given in a written form on the computer screen, encouraging participants to respond as fast and as accurate as possible. Each trial started with the presentation of a fixation cross (visual angle of 0.2°) at a visual angle of 5° left to the center of the screen for 50 ms followed by a blank screen for 500 ms. An isolated stimulus appeared for 1000 ms at the same position as the fixation cross before. After another blank screen, shown for 650 ms, the second fixation cross was shown for 50 ms at a visual angle of 5° right to the center of the screen, again followed by a blank screen for 500 ms. At the same position as the second fixation cross, the second stimulus was presented either isolated or surrounded until parti-

Participants gave their response by pressing the keys "s" with their left index finger or "l" with their right index finger of an external keyboard for "same" or "different", depending on the individual instruction. The assignment of the keys for "same" or "different" was counterbalanced across all participants. A blank screen appeared for 1000 ms, before the next trial started.

In each trial the two presented letters were from the same alphabet, meaning that e.g., a Latin letter was followed either by the same Latin letter or by another Latin letter. Altogether, participants performed 216 trials; 72 trials using Latin letters, 72 trials using Hebrew letters and 72 trials using Cyrillic letters. The trials were randomized across all participants.

4.2.2. Results

One participant was excluded from further analysis, because of an overall accuracy less than 80 %. From the remaining 40 participants error rates (ER) and reaction times (RT) of correct responses within an individual outlier criterion of $140 \text{ ms} < \text{RT} < 3000 \text{ ms} \mid M_i + 3.5SD_i$ (i = individual value; 100 trials were excluded, 0.1 % of all trials) were analyzed. The mean ER was 6.9 % ($SD = 4.2$ %) and ranged from 1.9 % to 19.2 %. The overall mean RT was 450 ms ($SD = 86$ ms) and ranged from 312 ms to 743 ms. Since there was a speed-accuracy trade off, $r(38) = .37$, $p < .02$, analyses for RT and ER are reported. The mean arcsin transformed ERs are illustrated in Figure 4.2; mean RTs are illustrated in Figure 4.3.

The RT data as well as the ER data (arcsin-square-root transformed) were analyzed in repeated measures 3 x 3 x 2 Analyses of Variance (ANOVA), with the factors *Material* (Latin letters, Hebrew letters and Cyrillic letters), *Congruency* (isolated, congruent and incongruent) and *Response type* (same and different). Interactions were analyzed in post-hoc ANOVAs and pairwise Bonferroni corrected t-tests.

For arcsin-transformed ERs we observed main effects for *Material*, $F(2, 78) = 7.06$, $p < .01$, $\eta_p^2 = .15$, as well as for *Congruency*, $F(2, 78) = 8.10$, $p < .001$, $\eta_p^2 = .17$. Post-hoc Bonferroni corrected pairwise t-tests for *Material* levels showed lower ERs for Latin letters (5.4 %) compared to Cyrillic letters

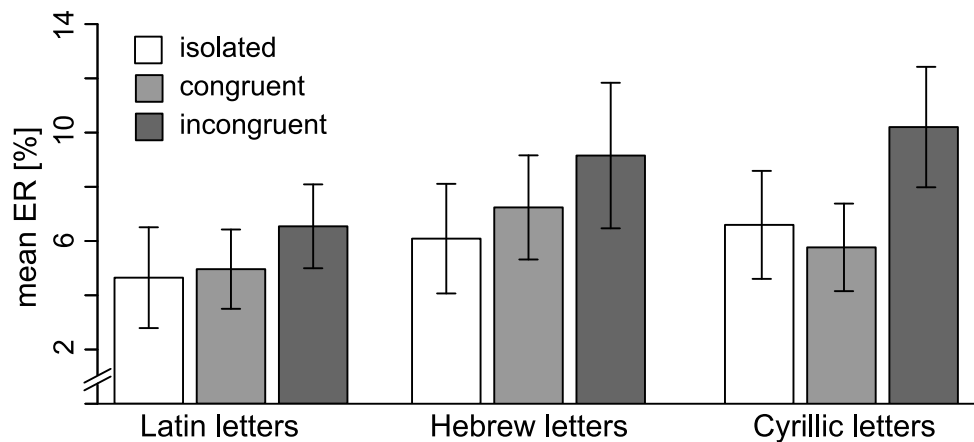


Figure 4.2.: Mean ERs for isolated, congruent and incongruent targets (from left to right in each block) for Latin letters (left), Hebrew letters (middle) and Cyrillic letters (right).

(7.5 %), $t(39) = 3.52$, $p < .01$, and Hebrew letters (7.5 %), $t(39) = 3.03$, $p < .01$, as well as higher ER for incongruent targets (8.6 %) than for congruent targets (6.0%), $t(39) = 3.09$, $p < .01$, and isolated targets (5.8 %), $t(39) = 3.36$, $p < .01$. Interactions were found between *Material* and *Response type*, $F(2, 78) = 10.17$, $p < .001$, $\eta_p^2 = .21$, and between *Congruency* and *Response type*, $F(2, 78) = 5.82$, $p < .01$, $\eta_p^2 = .13$. Post-hoc analyses showed that for *different*-responses there were neither difference in ERs between the different letter groups nor between different kinds of congruency, $F(2, 78) < 1$. For *same*-responses ERs increased for Hebrew letters, $t(39) = 3.19$, $p < .01$, and for Cyrillic letters, $t(39) = 2.37$, $p < .05$ compared to the *different*-responses, whereas for Latin letters there were no differences in error rates, $t(39) 1.68$, $p = .10$. Furthermore, there was an increase of ERs for incongruent surrounded figures, $t(39) = 3.52$, $p < .01$.

Main effects for RT analyses were observed for all factors. For *Material*, $F(2, 78) = 49.42$, $p < .001$, $\eta_p^2 = .56$, responses were faster for Latin letters (436 ms) than for Cyrillic letters (457 ms), $t(39) = 7.06$, $p < .001$, and Hebrew letters (462 ms), $t(39) = 8.33$, $p < .001$. For *Response type*, $F(1, 39) = 25.07$, $p < .001$, $\eta_p^2 = .39$, there were faster responses for *same*- (437 ms) than for *different*-responses (466 ms), indicating the fast-same effect. For *Congruency*,

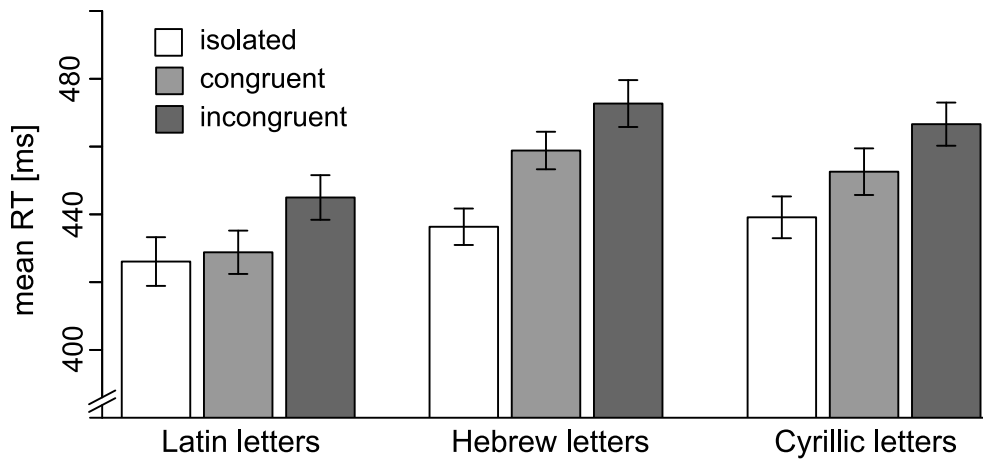


Figure 4.3.: Mean RTs for isolated, congruent and incongruent target (from left to right in each block) for Latin letters (left), Hebrew letters (middle) and Cyrillic letters (right).

$F(2, 78) = 54.27, p < .001, \eta_p^2 = .58$, with faster responses for isolated targets (438 ms), $t(39) = 4.72, p < .001$, than for congruent targets (451 ms), which were again faster than incongruent targets (467 ms), $t(39) = 6.23, p < .001$.

There was a *Material x Congruency* interaction, $F(4, 156) = 4.86, p < .01, \eta_p^2 = .11$. Post-hoc analysis showed that responses for isolated Hebrew letters were faster (436 ms) than for congruent surrounded ones (459 ms), $t(39) = 6.85, p < .001$, whereas the processing of Latin letters was not impaired by congruent surroundings, $t < 1$. The *Material x Response type* interaction, $F(2, 78) = 5.99, p < .01, \eta_p^2 = .13$, showed that the fast-same effect was larger for Latin letters (36 ms) than for Cyrillic letters (26 ms), $F(1, 39) = 5.24, p < .05, \eta_p^2 = .12$, and Hebrew letters (20 ms), $F(1, 39) = 5.24, p < .05, \eta_p^2 = .22$. The *Congruency x Response type* interaction, $F(2, 78) = 27.22, p < .001, \eta_p^2 = .41$, showed that the congruency effect only holds for *same*-responses, $F(2, 78) = 70.17, p < .001, \eta_p^2 = .64$. The fast-same effect was larger for isolated targets (46 ms) compared to congruent surrounded targets (29 ms), $F(1, 39) = 16.52, p < .001, \eta_p^2 = .30$, and congruent surrounded targets benefited more from the fast-same effect than the incongruent surrounded ones (7 ms), $F(1, 39) = 17.25, p < .001, \eta_p^2 = .31$.

4.2.3. Discussion

In Experiment 1, we used a same-different task with surrounded Latin letters and letters from other alphabets, acting as non-letters. Lachmann and van Leeuwen (2008a) observed for short ISIs (320 ms) a negative congruency effect for letters and a positive congruency effect for non-letters. For very large ISIs (2920 ms) this distinction vanished. The current experiment explored, whether this distinction is restricted to very short ISIs or holds also for larger ISIs (1200 ms), although twice as many non-letters as letters were presented. This imbalance was necessary, because this experiment also served as pilot study for a follow-up training study. To ensure that the results are reliable, independently of the used stimuli, we also tested different sets of non-letter material.

Beside the fast-same effects, which is typical for this kind of task, most observed effects are ascribed to low-level visual processes. Latin letters were detected faster and more accurately than Hebrew and Cyrillic letters, reflecting the higher familiarity for Latin letter compared to the other ones. This different familiarity also leads to the observed distinctions for same- and different-responses. Independently of material, isolated targets were processed faster than congruent surrounded ones and congruent surrounded targets were processed faster than incongruent surrounded ones, reflecting the positive congruency effect. This positive congruency effect is typical for simple shapes and indicates a context sensitive holistic processing.

In contrast to our hypothesis, congruency effects were observed for Hebrew and Cyrillic letters as well as for Latin letters. The only distinction was observed between Latin and Hebrew letters for isolated and congruent surrounded targets. Considering that for this specific interaction Cyrillic letters, did neither differ from the Latin nor the Hebrew letter set, this result is barely interpretable. Perhaps it is just caused by different degrees of similarity between the targets and the congruent surroundings, leading to unpredictable side-effects (see also Lachmann & van Leeuwen, 2008a).

Our results closely resembled the findings of Lachmann and van Leeuwen (2008a) for large ISIs, indicating that the appearance of letter-specific processing strategies depends on the rate of stimulus presentation. Whereas Lachmann and

van Leeuwen (2008a) demonstrated that the negative congruency effect for letters vanishes for very long ISIs, the current results suggest that this holds also for remarkable shorter ISIs. Hence, the current results extend prior findings by restricting the appearance of letter-specific processing strategies to very fast stimulus presentation rates. After a time range of 1200 ms, the categorial influence of letters seems to be completely eliminated and letters as well as non-letters are processed uniformly in a holistic feature integration mode. On the one hand, this result is in accordance to a highly automatized letter processing strategy which, especially, is effective for stimuli appearing at a relatively fast rate (Lachmann & van Leeuwen, 2008a). On the other hand, in Lachmann and van Leeuwen (2008a) the typical letter effects also were observed for an ISI of 1200 ms. The contrasting result might be caused by an imbalance in our experimental design. If non-letters are presented twice as often as letters, this may tip the balance in favor of a holistic strategy. However, since analytic processing was observed even for an imbalanced design for a shorter ISI of 320 ms (Lachmann & van Leeuwen, 2008a), it can be assumed that the holistic processing replaces the analytic processing of letters not completely. The effects of analytic processing are just reduced by the impact of the holistic strategy.

Although our results extend prior findings, our original intention was to explore a paradigm, showing a reliable letter versus non-letter distinction. Since under the chosen conditions the expected negative congruency effect for letters vanished, this paradigm could not be used. Our results suggest that paradigms, using surrounded letters, are too task- and context-sensitive with regard to the aim of further studies. Nevertheless, congruency effects seem to be a good approach to explore distinguished processing of letters and non-letters. Hence, in the following experiment, we explored a paradigm, using a different kind of contextual embedded figures.

4.3. Experiment 2: The influence of reading-like conditions on Global Precedence Effect in letters and non-letter shapes

The assumption of analytic letter processing strategies predicts that letters are less sensitive for context effects. For example, as we expected in Experiment 1, Latin letters should not be influenced by congruent or incongruent surroundings. This seems to be in contrast to the well-known *Global Precedence Effects* (GPE) (see Chapter 2.5), which predicts that perception of the global level of hierarchical, compounded figures – so called Navon letters (Navon, 1977) – influence the processing of the local level elements. However, there are reasons to expect differences in letter and non-letter processing in paradigms using these Navon figures under special more reading-like conditions. Letters are normally processed under these conditions, meaning central presentation and a special combination of visual angles for the global and the local level. Therefore, these conditions should benefit the appearance of letter-specific processing strategies (see Chapter 2.5).

Since, most studies used either letter or non-letter material, but no study varied systematically the visual angle for both kinds of stimuli, we can only assume a distinction of GPE by comparing different studies. Therefore, in *Experiment 2* we presented both, letter and non-letter Navon figures, under these reading-like conditions, assuming that the GPE is still robust for non-letter Navon figures but vanishes for letter material.

Hypothesis 2. *Under reading-like conditions the GPE is still robust for non-letter Navon figures, but vanishes for letter material.*

Besides our actual intention to explore a reliable paradigm, which could get used in a following training study this experiment should extend prior findings of contextual embedded figures to the GPE. Whereas the prior experiment showed constrains, considering the time course of letter processing, the current experiment should give evidences for perceptual constrains under which letter-specific processing could be observed in a more reading-like context.

4.3.1. Method

Participants

Thirty-seven students (16 female, $M_{age} = 26$ years, $SD_{age} = 3$ years), all German native speakers, from the University of Kaiserslautern, Germany, were paid for their participation. All participants reported normal hearing and normal or corrected-to-normal vision, and were not diagnosed as having any reading disorder. Participants signed consent forms prior to the study. The study was approved by the ethical committee of the Faculty of Social Science of the University of Kaiserslautern.

Material

Eight compound, hierarchical figures were used, as illustrated in Figure 4.4. Four of them were letters at the global level composed of letters at the local level (C or F) and the other four were non-letters composed of non-letter shapes. Half of both were congruent, i.e., a global level composed of smaller versions of the same (e.g., a large C composed of small Cs or a large non-letter shape composed of small versions of the same shape); the other half were incongruent, i.e., global and local levels were different (e.g., a large C composed of small Fs or a large non-letter shape composed of small versions of a different shape). Letter and non-letter stimuli were of similar visual complexity. The global stimuli appeared with a visual angle of approximately 6.5° in height and 5.5° in width, the local stimuli with a visual angle of approximately 0.5° . Another non-letter set as in Experiment 1 was used to minimize similarity with well-known Latin letters.

All stimuli were presented in black (0.4 cd/m^2) against a white background (28.9 cd/m^2) on a 15" laptop screen running Windows XP and E-Prime 2.0 (Psychology Software Tools, Pittsburg, USA).

Procedure

The experiment consisted of four blocks: two blocks with letters and two blocks with non-letters. In half of the blocks, participants responded to the global figure regardless of the local components (global condition), and vice versa in the other

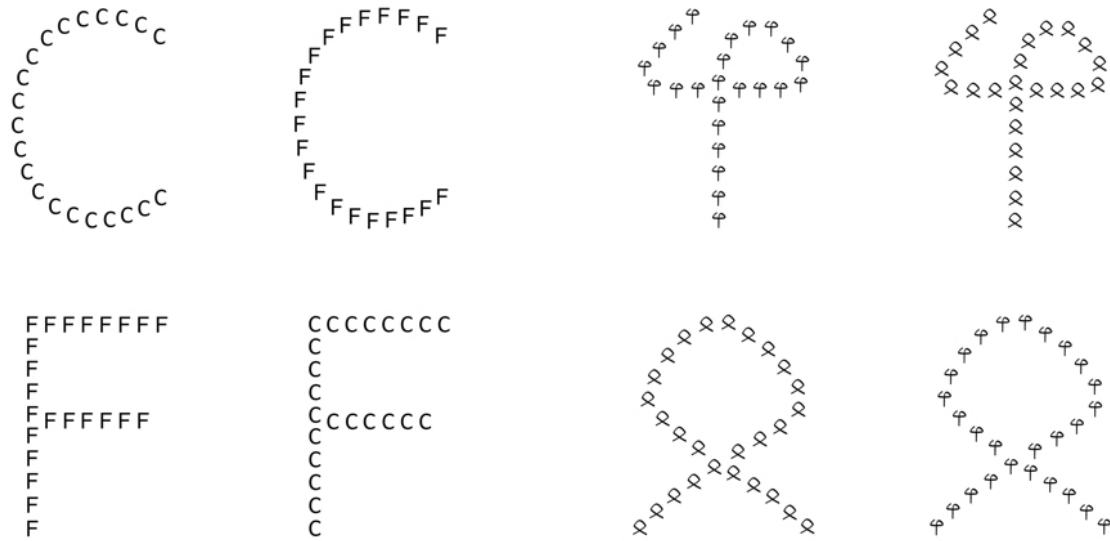


Figure 4.4.: The compound, hierarchical figures, build-up of Latin letters (left) or non-letter shapes (right), could either be congruent (column 1 and 3) or incongruent (column 2 and 4)

half (local condition). The order of the four blocks was randomized across participants. Each of the blocks contained 100 trials, half with congruent and half with incongruent stimuli in random order. Participants performed a two-alternative forced-choice identification task (2AFC) by pressing the left or right button of the embedded laptop mouse with their index fingers. Response conditions changed between blocks (e.g., level = local: F = right key, C = left key) and were counter-balanced between participants.

Each trial started with a fixation cross displayed for 250 ms at the center of the screen, followed by a blank screen for 250 ms. After this, the stimulus was presented at the fixation location and remained visible until either the participant responded or 2000 ms had passed. After another 250 ms blank screen, the next trial started. Prior to each block eight practice trials were presented, each followed by visual feedback (correct / incorrect) lasting for 500 ms.

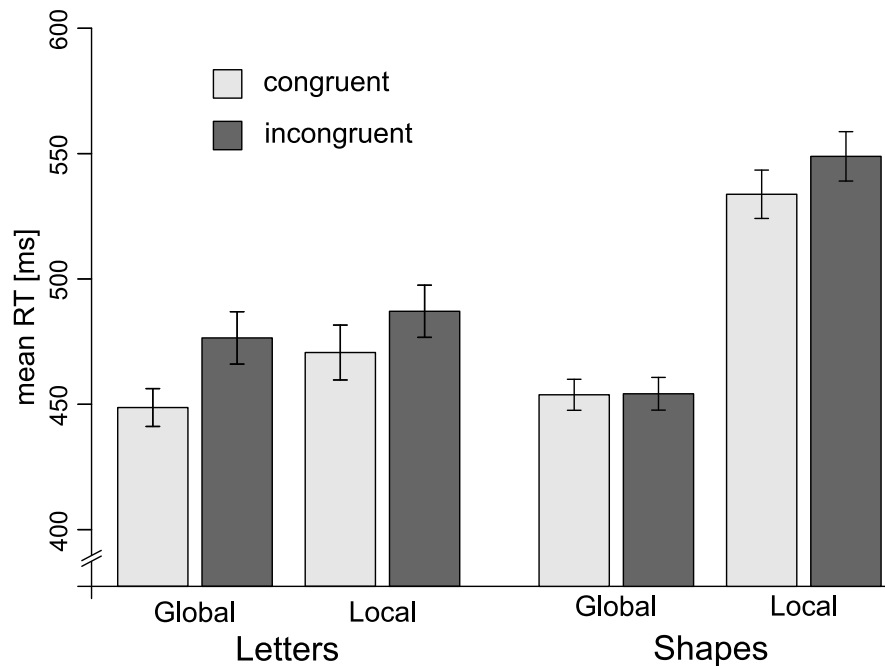


Figure 4.5.: Mean RT in ms for letter stimuli (left side) and non-letter stimuli (right side) for congruent and incongruent trials in the local and global blocks.

4.3.2. Results

Error Rates (ER) and reaction times (RT) of correct responses within a range of 200-2000 ms were analyzed. No outliers needed to be excluded. Since, there was no evidence for a speed-accuracy trade off, $r(35) = 0.3$, *n.s.*, in the following sections we will report RT analyses only. The RT data were analyzed by a repeated measures 2 x 2 x 2 Analysis of Variance (ANOVA) with the factors, *Material* (letters or non-letter shapes), *Level* (global or local target), and *Congruency* (congruent or incongruent). As a preliminary analyses showed, there were no differences between individual letters or shapes within the letter or non-letter condition. Mean RTs for all conditions are displayed in Figure 4.5.

Main effects were observed for *Material*, $F(1, 36) = 9.76$, $p < .001$, $\eta_p^2 = .21$, with faster RTs for letters (471 ms) than for non-letter shapes (498 ms), for *Level*, $F(1, 36) = 58.04$, $p < .001$, $\eta_p^2 = .62$, with faster responses for the global (458 ms) than for the local level (510 ms) targets and for *Congruency*, $F(1, 36) = 38.06$,

$p < .001$, $\eta_p^2 = .51$, with faster responses for congruent stimuli (477 ms) compared to incongruent ones (492 ms).

There was a two-way interaction for *Material* x *Level*, $F(1, 36) = 18.21$, $p < .001$, $\eta_p^2 = .34$, showing that the difference in mean RTs between global and local targets was larger for non-letter shapes (87 ms) than for letters (16 ms). Furthermore, we observed a two-way interaction *Material* x *Congruency*, $F(1, 36) = 6.94$, $p < .05$, $\eta_p^2 = .16$, showing that the congruency effect was larger for letters (22 ms) than for non-letter shapes (8 ms). There was a three-way interaction between *Material*, *Level* and *Congruency*, $F(1, 36) = 6.74$, $p < .05$, $\eta_p^2 = .16$, showing a distinction of the congruency effect between letters and non-letter shapes, depending on the target level. Due to this three-way interaction, we then analyzed the data separately for letters and for non-letters.

For non-letters, we observed main effects for *Level*, $F(1, 36) = 54.41$, $p < .001$, $\eta_p^2 = .60$ (*global advantage effect*), with faster responses for the global (454 ms) than for the local level (541 ms) and for *Congruency*, $F(1, 36) = 7.43$, $p < .05$, $\eta_p^2 = .17$ (*congruence effect*), with faster responses to congruent (494 ms) compared to incongruent targets (502 ms). Furthermore, there was an interaction between *Level* and *Congruency*, $F(1, 36) = 5.47$, $p < .05$, $\eta_p^2 = .13$, with interference from the global to the local level, $t(36) = 3.01$, $p < .01$, but no interference from the local to the global level, $t(36) < 1$, $p = .90$ (*asymmetric congruence effect*).

For letters, there was only a main effect for *Congruency*, $F(1, 36) = 26.53$, $p < .001$, $\eta_p^2 = .42$, with faster responses for congruent (460 ms) than for incongruent targets (482 ms). In contrast to non-letter shapes, there was neither an effect for *Level* $F(1, 36) = 2.92$, $p = .096$, $\eta_p^2 = .07$ nor a *Level* x *Congruency* interaction, $F(1, 36) = 2.56$, $p = .118$, $\eta_p^2 = .07$, but instead a both-sided interference from the local level when attending to the global targets, $t(36) = 5.06$, $p < .001$, and from the global level when attending to the local targets, $t(36) = 2.91$, $p < .01$.

4.3.3. Discussion

In Experiment 2 we investigated the GPE for compound figures, expecting, that under "specific conditions" the GPE vanishes for letters but stays robust for non-

letter shapes. Specific conditions means in fact, that the stimuli were presented centrally with a specific combination of visual angles for the global level and the local elements.

Central presentation is a necessary condition for the expected differentiation between letters and non-letters to occur (Plomp et al., 2010). As demonstrated in eye-movement studies using gaze-contingent display change techniques (Rayner et al., 1986), graphemic (phonological), morphological or lexical decoding and identification is limited to what is centrally present during a fixation, typically a word (see Pollatsek, 1993, for an overview). The combinations of visual angles was a result of comparing observations on the GPE from previous studies, showing that for letters the GPE could be observed for small visual angles, but disappears and even inverts for larger visual angles. A survey of the literature gave evidence that for a visual angle of approximately 0.5° for the local elements, which is very close to that of single letters in fluent reading (Jordan & Martin, 1987; Legge et al., 1985), there should be a distinction between letters and non-letters. The global level with a visual angle of approximately 6.5° fall within the functional visual field (Sanders, 1970), matching the size of a whole word in fluent reading. However, there was no study comparing Navon figures build-up of letters or non-letters under these specific conditions, which we assumed to be crucial for activation of letter-specific processing as a consequence of automatized reading skills.

Confirming Hypothesis 2 the GPE remained intact for non-letter stimuli but disappears for letters under the chosen conditions. For non-letters the general *advantage for the global stimuli* could be observed, as well as the *asymmetric congruence effect*, showing interference from the global to the local level, but not vice versa. In contrast, for letters there was neither a *global advantage* nor an *asymmetric congruence effect*, but the congruence effect was independent of target level.

Since the GPE vanished only for letters, we interpret these results as new evidences for a letter-specific strategy, which is also applied to these kinds stimuli. We could transfer the findings from prior studies, showing a distinction in congruency effects between letters and non-letters, to the GPE in Navon figures, as long as the stimulus dimensions invite a reading-specific strategy. Since the automatization of letter processing mostly occurs under reading conditions, it is obvious

that the impact of automatized processing is greatest under these conditions. As explained in Chapter 2.5.7, we assume a more analytical letter processing strategy, whereas the earlier developed object recognition strategy for non-letter shapes may be holistic.

One characteristic of the analytic letter strategy is less context sensitivity for letters compared to that for non-letters (Lachmann, Schmitt, Braet & van Leeuwen, 2014; Lachmann & van Leeuwen, 2004, 2008a; van Leeuwen & Lachmann, 2004). This seems to be in contrast to our findings, considering that for letters we found an interference for the global as well as for the local level. Nevertheless, the GPE normally shows an asymmetric congruency only from the global to the local level, but for letters there is also an interference from local to global. Thus, for letters the single elements have a much larger influence than non-letter shapes on processing hierarchical, compound figures. Therefore, the results are consistent with our view of a more analytical strategy for letters, which leads to a stronger focus on local elements compared to a holistic processing of the whole structure.

To understand the interaction between holistic and analytic processing in this paradigm, we have to differentiate the term "holistic" in the context of letter and word processing, in contrast to "holistic" processing of non-letter shapes.

Ehri (1995) emphasized that whole word reading in skilled readers is different to that what could be observed in the pre-alphabetic or logographic phase (Frith, 1986). During this phase of reading acquisition, words are perceived and recognized as a whole structure without considering a grapheme-phoneme relation. Children in the pre-alphabetic phase, who are able to "read" environmental prints, e.g., the logo of PEPSI, fail to notice the change, if one letter is altered (e.g., PEPSI in XEPSI; Masonheimer et al., 1984). Their reading is based on detecting single salient visual cues, as for example, the color combination and scripture of Coca-Cola instead of the initial letter C and the final letter a.

During the partial alphabetic phase, letters as an indicator of word recognition become more important (Ehri, 1995). During this stage, the letters are perceived as typical parts of a specific word, symbolizing sounds in that word. A full understanding of grapheme-phoneme relation is acquired during the full alphabetic phase, in which readers are able to transform unfamiliar spellings of words into blended pronunciation. This results in the consolidated phase which

enables readers for what we call whole word reading. However, compared to the pre-alphabetic phase, skilled readers do not perceive words as a whole structure, but as a combination of graphemes, morphemes and syllables. Thus, the holistic whole word reading includes also the segmentation of words in smaller units and not just a perception of words as a whole structure.

This parallel processing of the letter and word level could additionally explain, why in our Navon paradigm there was a congruence effect also from the local to the global level for letter stimuli. Otherwise, if the global level was perceived as a whole structure without considering the local level, there would have been an interference only from the global to the local level as we observed for the non-letter shapes.

Although, we do not claim that our conditions closely resemble those of reading, we could assume that the acquisition of these letter-specific processing strategies benefits from reading-like conditions and that these results may be considered as a small but important step in extending our earlier results to contextually embedded letters.

Most studies using either letter or non-letter Navon figures are in line with our results. However, there are only a few studies comparing letters and non-letters, e.g. Dulaney and Marks (2007) using peripheral presentation and Peressotti et al. (1991), who only varied letter and non-letter stimuli at the global level. Their studies did not involve a systematic comparison of the GPE in letters and non-letter shapes in both levels of Navon figures under central presentation. To our knowledge, this has only been done in a study by Poirel, Pineau and Mellet (2008) and an EEG follow-up (Beaucousin et al., 2011), showing that the GPE only appears for meaningful stimuli (e.g., letters) but not for meaningless stimuli (e.g., random scribbles). This seems to be in contrast to our results. A possible explanation could be that they used a relatively large visual angle (1° for local elements and 11° for the global level). It is also possible that the distinctions between letters and non-letters are task-sensitive. In our experiment, participants only have to differentiate between two given letters or shapes, whereas in Poirel's paradigm participants had to decide whether or not they detect a pre-designated target, which should benefit well-known letters in contrast to unknown scribbles. However, this contradiction requires further research, which was done in Study 3 (see Chapter 6).

Nevertheless, to come back to our original intention of the current study to explore a reliable paradigm for our following training study, the used global-local paradigm seems to satisfy this aim.

4.4. General Discussion

Both experiments gave new valuable evidences for letter-specific processing strategies. Experiment 1 restricted temporal constraints under which negative congruency effects for letters occur in so-called flanker tasks. Lachmann and van Leeuwen (2008a) observed the letter-specific effects for a relatively large ISI of 1200 ms in a same-different tasks. Experiment 1 demonstrated that this effect vanished, if the holistic processing gets additionally benefited by the experimental design. This finding does not contradict to the prior results. If non-letters are presented twice as often as letters the holistic object recognition is preferred. Hence, the effect of the automatized analytic letter processing is suppressed. However, since the results of Lachmann and van Leeuwen (2008a) demonstrated, they are not completely absent. Only the time course in which the effects occur is more restricted than in a more balanced experimental design. We assume that the holistic as well as the analytic strategies are not independently processed. The balance of these strategies depends on the specific requirements of the task. Nevertheless, the fact that the negative congruency effects for letters vanished completely for an ISI of 1200 ms, underlies the assumption that automatized letter processing is integrated in a very early stage of perceptual processes.

In addition to these temporal constraints on letter processing, Experiment 2 gave evidences for visual-perceptual constraints, which determine the appearance of letter-specific effects. Prior studies suggested that also in global-local tasks there are differences between letter and non-letter processing, depending on the chosen conditions. We demonstrated that reading-like conditions seem to benefit the usage of specialized strategies for letters. Obviously, this observation is caused by the fact that automatization of letter processing occurs under the same conditions. According to the functional coordination model (Lachmann & van Leeuwen, 2014; see also Chapter 2.2.1), automatization is the last stage of reading devel-

opment, when more advanced readers use their acquired reading skills in a more natural reading context. Since training is very context sensitive also the occurrence of the automatized strategies should show this context sensitivity. Hence, the chosen reading-like condition benefits the analytical processing for letters. However, this result seems to be in contrast to prior results (e.g., Beaucousin et al., 2011; Poirel, Pineau & Mellet, 2008), which showed that the GPE appears for letters but vanishes for non-letters. This contradiction will be the subject of Study 3. Simultaneously, we will try to answer, whether the observed distinctions between letters and non-letters are caused by meaningfulness or letter-specific processing strategies.

Whereas the current results have given some external constraints for letter processing, the latter paradigm will be used to explore some more internal constraints. Although, we assume that the distinction between letters and non-letters is caused by different processing strategies, in principle, it could only be a result of different familiarity. We will compare both approaches in the following training study.

5. Study 2: Training study: Can letter-specific processing be transferred?

5.1. Aim of the study

The theoretical prediction that letters are preferably processed analytically is based on the assumption that this strategy is the result of extensive practice of a GPC. Here, we raise the question whether such an association can be induced in normal adult readers also for non-letter shapes. We address this issue with a training study, in which participants learn phonological associations to non-letter shapes (*phonological training*). If these associations constitute the core of letter-specific processing, the training should turn non-letters into the processing equivalent of letters. As a consequence, the global precedence for these non-letters is expected to disappear after training.

However, such an effect could, in principle, also be explained by increased familiarity of the shapes as a consequence of training. For this reason, a second training condition was added, in which the same non-letter shapes became associated with non-phonological auditory stimuli (*non-phonological training*). If the effect of training is based on familiarity, it should occur in both of the training conditions. A result in accordance with familiarity would require a modification of the reading theory, in order to explain how familiarity alone could enhance analytic processing. A third possibility is that the training will have no effect in either condition. Various factors could be responsible for such a result, all of which would offer challenges to the reading theory. For instance, it should then

be argued why learning a restricted set of pairwise associations is not sufficient to induce the analytic strategy in adult readers.

Hence, this study allows us to test three mutually contradictory hypotheses in parallel.

Hypothesis 3. *If GPC constitute the core of letter-specific processing, in the following posttest, the GPE for non-letters vanishes only for the phonological training group.*

Hypothesis 4. *If the different effects for letters and non-letter shapes are caused by familiarity, in the following posttest, the GPE for non-letters for both groups vanishes.*

Hypothesis 5. *If neither familiarity nor simple GPC is sufficient to induce the analytic strategy in adult readers, the GPE for non-letters remains for both groups.*

5.2. Method

5.2.1. Participants

Seventy-five students (between 19 and 29 years old) from the University of Kaiserslautern, Germany, were paid for their participation in this study. All participants were skilled readers of German and/or English with normal hearing and normal or corrected-to-normal vision. None of them was diagnosed as having any reading or writing disorder. Participants were randomly assigned to one of two training conditions, a phonological training group ($N_p = 36$) and a non-phonological training group ($N_{np} = 39$). Participants signed consent forms prior to the study. The study was approved by the ethical committee of the Faculty of Social Science of the University of Kaiserslautern.

5.2.2. Material and Procedure

For the *pretest* and *posttest* the Navon figure paradigm as described in chapter 4.3.1 was used. Hence, here only the *training part* is explained.





				
corresponding phonological sounds	/a:/	/i:/	/f/	/s/
corresponding non-phonological	horn#3	trumpet (D4)	pink noise	brown noise

Figure 5.1.: Non-letter shapes used in the training part and their corresponding phonological sounds (upper part) and non-phonological sounds (lower part).

During the training, participants established associations to four non-letter shapes: two slightly enlarged versions of the non-letter components from the *pretest* (left side of Figure 5.1) and two novel ones (right side of Figure 5.1). Novel shapes were introduced, in order to enable sufficient variation as required by some of the subtasks of the training (see below). Some of these subtasks presented a single shape in isolation; others involved strings of two, three, or four shapes. In all these cases a single shape was approximately 1.5° in height and width. The visual angle was approximately 3° in width for a two-shapes string, 5° for a three-shapes string, and 7° for a four-shapes one. All visual stimuli were presented in black (0.4 cd/m^2) against a white background (28.9 cd/m^2) on a 15" laptop screen running Windows XP and E-Prime 2.0 (Psychology Software Tools, Pittsburg, USA). There was no fixation of the head.

Between participants, two different training conditions were imposed. In the phonological condition, one of four phonemes /a:/, /i:/ (vowels), /f/, and /s/ (consonants) was assigned to one of the four non-letter shapes, as illustrated in Figure 5.1 (upper part). Duration and intensity of the phoneme stimuli were adjusted with Adobe Audition CS5 (Adobe, San Jose, USA), such that all had the

same length (300 ms) and intensity (70 dB). Vowels and consonants were combined into phoneme-sequences of 600 ms duration for two, 900 ms for three, and 1200 ms for four phonemes, corresponding to the visual strings of different lengths. In the non-phonological condition, sounds physically similar to the speech stimuli were used (see Figure 5.2). Instead of the consonants /f/ and /s/, pink and brown noise were presented, respectively, and instead of the vowels /a:/ and /i:/, two musical tones, one from a horn (A#3) and the other one from a trumpet (D4) (see Figure 5.1 lower part) were used, respectively. The sounds were generated with Adobe Audition CS5. For visual strings, the corresponding tones were combined in a similar fashion as for speech stimuli of the same length.

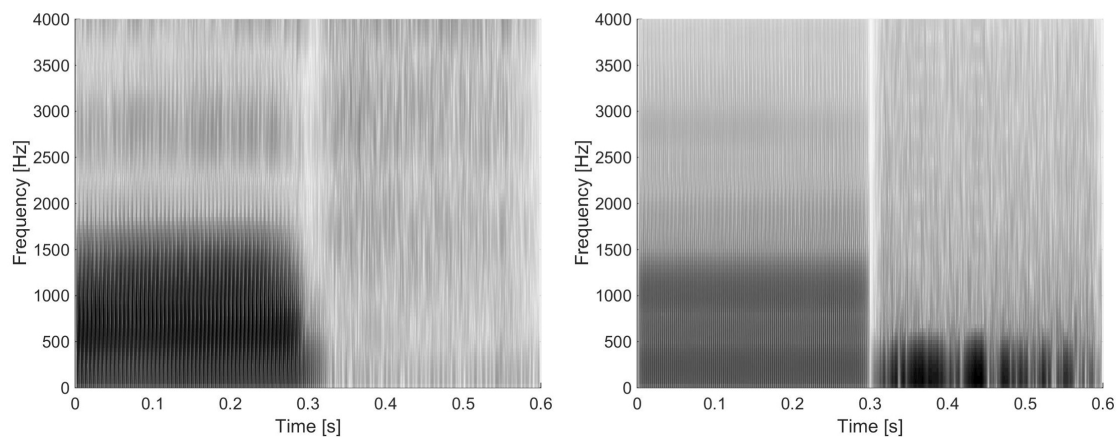


Figure 5.2.: Spectrograms for the vowel /a:/ and the fricative /f/ (left), and their corresponding non-phonological sounds trumpet sound and pink noise (right). Time is displayed on the horizontal axis, and frequency (in Hz) on the vertical axis. The shade of grey represents the intensity of each frequency, with darker shades corresponding to higher intensities.

Apart from the auditory stimuli, both groups went through identical training procedures. Three training sessions were performed on separate days. During the training, the following tasks were used: *association*, *writing*, *short sequences* and *long sequences*.

In the *association task*, a single shape was presented on the screen while the corresponding sound was played three times in succession. Participants were instructed to pay attention and remember the pairing of auditory and visual stimuli. After all four combinations were presented once and then repeated in the same

order, participants performed a sequence of 258 probe trials. Each trial started with a 1 s visual presentation of the instruction: *"identify the following sound"*, followed by the sound, after which a cursor (a cross) appeared at the center of the screen, surrounded by all four shapes arranged randomly according to Figure 5.3. Participants were asked to move the cursor with the computer mouse and click on the character corresponding to the sound. After a correct response, the next trial started immediately; following an error, feedback was displayed for 1 s, showing the phrase *"The correct response was:"* together with the correct shape, simultaneously with the corresponding sound. Afterwards, the next trial started immediately.

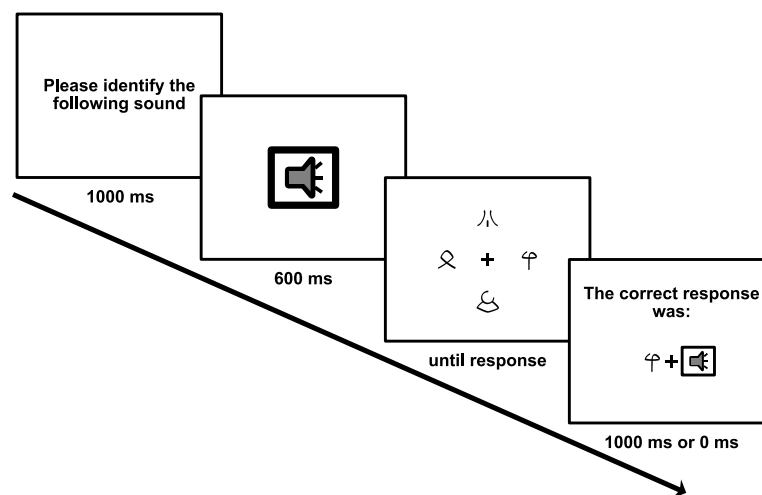


Figure 5.3.: The sequence of a trial in the training tasks. Participants identified the character (or sequence of characters) that corresponds to the (sequence of) sound(s) that was just played.

The *writing task* consisted of 50 trials according to the same procedure as the association task, except that participants wrote down their responses, after which they started the next trail by pressing a mouse button. No feedback was given.

The *short-string-task* used instead of a single sound, short sequences of either two (in 15 trials) or three (in 36 trials) sounds. Participants choose the corresponding string from four response alternatives (three distracters were randomly chosen from the stimulus set). Otherwise, the trials are identical to those of the

association task. The *long-string task* (45 trials) used sequences of four sounds and corresponding strings of four non-letter shapes.

Each session started with the *association task*. This task, therefore, occurred three times during the training. Other tasks each were performed twice. Their order was randomized, with the following constraints: none of the tasks could occur twice in a session and in the first session, the *short-string* task was presented immediately after the association task.

5.3. Results

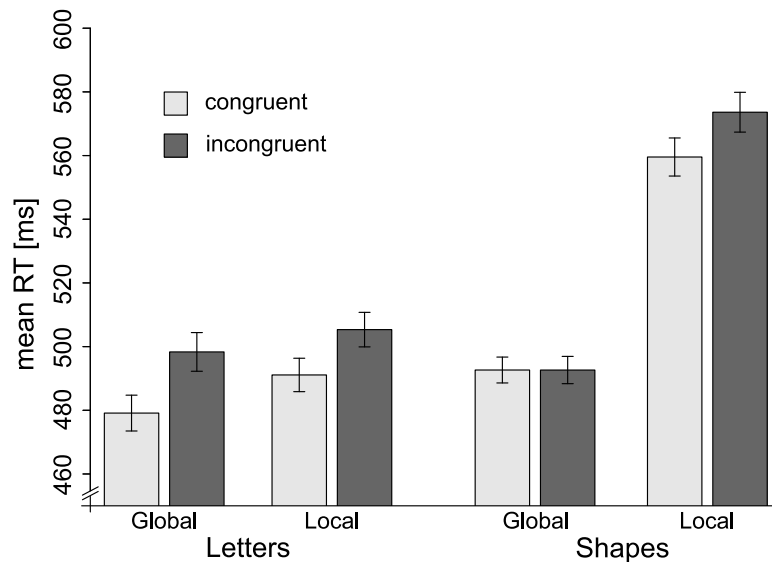


Figure 5.4.: Mean RT in ms for letter stimuli (left side) and non-letter stimuli (right side) for congruent and incongruent trials in the local and global blocks.

Error rates (ER) and Reaction times (RT) of correct responses within an individual outlier criterion $150 \text{ ms} < \text{RT} < 2000 \text{ ms} \mid M_i + 3SD_i$ (i = individual value; outliers: 912 trials, 1.8 % of all trials) were analyzed. The data from eleven participants was excluded from further analyses because of an ER higher than 50 % in at least one factorial cell. The overall mean ER of the remaining 64 participants was 3.2 % ($SD = 2.8$ %) and ranged from 0.1 % to 11.7 %. The overall mean RT was 497 ms ($SD = 67$ ms) and ranged from 350 ms to 609 ms. Since there was no

evidence for a speed-accuracy trade off, $r(62) = .12$, *n.s.*, in the following sections we will report RT analyses only.

The RT data were analyzed in a mixed $2 \times 2 \times 2 \times 2 \times 2$ ANOVA with *Material* (letters vs. non-letter shapes), *Level* (global vs. local), *Congruency* (congruent vs. incongruent), *Phase* (pretest vs. posttest) as within-participants factors and the between participants factor *Group* (phonological vs. non-phonological group). Preliminary analyses showed no differences between individual letters or shapes within the letter or non-letter condition, respectively.

Mean RTs for the conditions are displayed in Figure 5.4. Main effects were observed for all within-participant factors: *Material*, $F(1, 62) = 111.24$, $p < .001$, $\eta_p^2 = .64$, with faster reactions for letters (480 ms) than for non-letter shapes (520 ms); *Level*, $F(1, 62) = 153.15$, $p < .001$, $\eta_p^2 = .71$, with faster responses for global (470 ms) than for local level targets (520 ms); *Congruency*, $F(1, 62) = 101.80$, $p < .001$, $\eta_p^2 = .62$, with faster responses for congruent stimuli (494 ms) than for incongruent stimuli (504 ms); and *Phase* $F(1, 62) = 12.04$, $p < .001$, $\eta_p^2 = .16$, with faster responses for the posttest (493 ms) compared to the pretest (506 ms).

There was a two-way interaction between *Material* and *Level*, $F(1, 62) = 92.82$, $p < .001$, $\eta_p^2 = .60$, showing, that the difference in RT for the local and the global level was smaller for letters (11 ms) than for non-letters (71 ms). An interaction between *Material* and *Congruency*, $F(1, 62) = 19.74$, $p < .001$, $\eta_p^2 = .24$, indicated a larger congruency effect for letters (15 ms) than for non-letters (7 ms) and an interaction between *Level* and *Congruency*, $F(1, 62) = 10.84$, $p < .01$, $\eta_p^2 = .15$, showed on average a larger congruency effect for the local (15 ms) than for the global level (8 ms).

Additionally, a three-way interaction *Material* x *Level* x *Congruency*, $F(1, 62) = 42.21$, $p < .001$, $\eta_p^2 = .41$ was found. In post-hoc analyses, the *Level* x *Congruency* interaction was analyzed separately for non-letters and letters.

For non-letters, we confirmed the general observation of faster responses for the global (484 ms) than for the local level (555 ms; *global advantage*), $F(1, 63) = 225.73$, $p < .001$, $\eta_p^2 = .78$, and faster responses for the congruent (516 ms) than for the incongruent stimuli (523 ms; *congruency effect*), $F(1, 63) = 24.96$, $p < .001$, $\eta_p^2 = .28$. The interaction between *Level* and *Con-*

gruency, $F(1, 63) = 51.33$, $p < .001$, $\eta_p^2 = .45$, results from a negative impact of global incongruency on the local targets, $t(63) = 7.16$, $p < .001$, in absence of an effect of local incongruency on global targets, $t(66) = 1.56$, $p = .12$.

For letters, we also confirmed faster RTs for the global (474 ms) than for the local level (487 ms), $F(1, 63) = 5.71$, $p < .05$, $\eta_p^2 = .08$, and for congruent (472 ms) compared to incongruent stimuli (487 ms), $F(1, 63) = 58.6$, $p < .001$, $\eta_p^2 = .64$. The interaction between *Congruency* and *Level*, $F(1, 63) = 4.06$, $p < .05$, $\eta_p^2 = .06$, revealed negative impacts of both global incongruency to the local level $t(63) = 7.17$, $p < .001$, and of local incongruency to the global level $t(63) = 7.92$, $p < .001$, of which the latter was larger in size (18 ms) than the former (13 ms). This is opposite the non-letter condition. No other effects were obtained. In particular, there were no *Group* effects, $F(1, 62) = 1.67$, nor interactions involving both *Group* and *Phase* (all $F(1, 62) < 1$, except one: $F(1, 62) = 1.66$).

5.4. Discussion

In this training study we tried to figure out evidences for specialized letter processing strategies, by investigating the GPE in compound figures before and after several training sessions. In our pre- and posttest we used a variant of the classical Navon-paradigm with central presentation and a specific size ratio of global and local levels of stimuli. In Study 1 we already showed, that under these conditions the GPE is still robust for non-letter shapes, but vanishes for letters.

Although we demonstrated that reading-like conditions seem to influence the processing of letters, the reason for this was still unclear. On the one hand, it could be caused simply by familiarity, meaning that detecting the well known letters is much easier than detecting the unfamiliar shapes and therefore the interference from one to the other level is larger. On the other hand, the reading-like conditions could trigger the mentioned specific processing strategy for letters which is developed during reading acquisition.

This present study should clarify the question what reason causes the disappearance of the GPE for letters; the familiarity or the letter-specific processing strategy. During the training, the phonological group learned to associate new non-letter shapes with phonemes, whereas the non-phonological group learned to

associate the shapes with non-phonological sounds. That means, the familiarity should increase for both groups, however, only the phonological training group should transfer letter-specific processing strategies to the non-letter shapes. If familiarity causes the difference in our paradigm, the GPE for both groups should increase, whereas if letter-specific processing strategies are the reason for this increase only the phonological group should show a different effect.

Both pre- and posttest replicated the global precedence for non-letters observed in Study 1 (Chapter 4.3). Non-letters persistently showed both components of the global precedence effect in RTs: the *global advantage* and an *asymmetric interference* of congruence (interference from the global to the local level but not vice versa). This result was taken as evidence of holistic processing of the non-letter stimuli both before and after training.

The decrease of RT in the posttest as compared to the pretest suggests that familiarity has effectively been raised for the non-letters. The persistence of holistic processing offers clear evidence against the view that *familiarity* is sufficient for inducing an analytic strategy (*Hypothesis 4 failed*). According to the predictions of the reading theory, holistic processing should be reduced as a result of the phonological training, as opposed to a non-phonological training. However, holistic processing persisted in both groups equally. This suggests that pairwise association learning involving a few non-letter shapes is not sufficient to induce the reading-specific strategy for these shapes in adults (*Hypothesis 3 failed*). In fact, neither familiarity nor phoneme association are sufficient explanations for the observed letter versus non-letter distinction (*Hypothesis 5*).

One reason that the training has failed to induce the reading-specific strategy for the non-letter shapes could be that between the pre- and posttest, the conditions were identical. It is possible that the pretest has established a categorical distinction between letters and non-letters that overrules the effects of the training. Further experiments, in which the pre- and posttest differ more strongly from each other, will enable us to test this hypothesis.

A more challenging possibility would be that the fully automatized reading skills, in particular the analytic processing of letters, cannot be transferred in adult readers to a new set of symbols, merely by training a few isolated pairwise associations. The fact that we can easily read a text in which a few letters are

systematically substituted with arbitrary symbols does not mean that these symbols take the role of letters, as the context provides disambiguation. In favor of this hypothesis speaks that it has taken particularly long to acquire the level of automatization in reading. However, for those who learned an alphabet, learning another one is relatively easy. Perhaps, in order to be effective, an entirely new alphabet needs to be trained rather than just a few items. This would be in agreement with the observation that reading is a systemic achievement, rather than the result of pairwise association. Finally, the training did not include semantic decoding. This all should be subject of further studies.

The neuronal recycling hypothesis of Dehaene and Cohen (2007) proposes, that during reading acquisition regions in the visual word form area, which are originally devoted to object recognition, are recycled to assume processes, which enable reading letters. It is not our aim to falsify this hypothesis, but our results show, that it is not that easy to transfer existing object recognition strategies to new learned shapes. Participants were able to identify the single items and combinations of these single items, depending on their phonological or non-phonological association. Hence, they seemed to be familiar with the new shapes after the training. However, they were not able to transfer their letter recognition and processing strategies to the Navon embedded figures task.

Such a highly developed strategy as letter processing should get easily transferred, but it takes a long time to automatize these strategies, even if it seems, transferring the reading ability to new learned letters is much easier. The automatization and the neuronal recycling must take place during a long-term training as it is given, e.g. during reading acquisition in elementary school.

The differentiation in the global precedence effect between non-letter shapes and letters as observed in Study 1 (Chapter 4.3) is replicated here with a considerably larger number of participants than previously. For letters, in Study 1 we obtained neither global advantage, nor an asymmetric interference. Here, the letter condition showed a global advantage. This effect, however, was considerably smaller than in the non-letter condition. Moreover, it does not qualify as holistic processing; there was an asymmetric interference effect in the opposite direction compared to the non-letter stimuli, with larger interference from the local to the

global level than vice versa. As a result, even though it takes a slightly different form than in Study 1, a differentiation between letters and non-letters is still observed in the present results. The two effects observed here for letters are rather small, and disappear when either the pre- or posttest are analyzed in isolation. The previously observed null effects in Study 1 could therefore be attributed to lack of power.

Hence, the effects observed here for the letter condition allow a more detailed interpretation of analytic processing in letters. On the one hand, the global advantage shows that items are more easily processed at a scale suitable for whole words than at the level of single letters. On the other hand, the asymmetric interference effect shows a strong influence of the local components to the overall processing. We may interpret this result as part of an automatized reading-specific strategy, which involves fast processing of local letters, functional for inferring the phonemic identity of a grapheme (Blau et al., 2010; Blomert, 2011; Froyen et al., 2009), as can be described by the non-lexical route in the DRC model (Coltheart et al., 2001). Local letter processing appears mandatory, even in the fast recognition of the global structure. By contrast, the global structure constrains local processing to a lesser extent.

These effects can only be understood by simultaneous processing of the global and local structure, where global processing constitutes the default recognition system at the scale of words. Simultaneous processing at the scale of letters, however, appears to be readily at hand, to intervene with the ongoing recognition process at word level. This interpretation is in accordance with the view that, at least for the current spatial dimensions of the local and global level, processing of the compound stimuli is performed in manner, similar to word reading.

To summarize, the current results support the idea of different processing strategies for letters and non-letter shapes, also in this special Navon paradigm. Although we ruled out the possibility that the observed distinction is only caused by differences in familiarity, however, there are still other possible explanations, causing the distinction, for instance, the influence of meaningfulness as predicted by Poirel, Pineau and Mellet (2008). Hence, this relation is one topic of the following study.

6. Study 3: Global Precedence Effect in children with poor reading abilities

6.1. Aim of the study

Poirel, Pineau and Mellet (2008) showed paradigms using Navon figures to be sensitive for the kind of chosen material. Hierarchical, compound figures with meaningful material (e.g., letters or pictograms of animals) lead to a GPE whereas stimuli using unknown shapes (e.g., pseudo-letters or random scribbles) do not lead to a GPE. This seems to be in contrast with our results from Study 1 in which we observed an opposite effect.

On the one hand, these observations can be explained by different paradigms, which require acquisition of working and long-term memory in different ways. In our paradigm participants had to differentiate between two appointed stimuli for a whole block, whereas in Poirel, Pineau and Mellet (2008) participants should decide if a stimulus contains a pre-designated stimulus which is different for each trial. This kind of paradigm obviously benefits familiar shapes. On the other hand, the stimuli in their paradigm are not within the reading-like conditions, which are essential for our explanation of the results of Study 1 and 2 (see Chapters 4.3 and 5).

Similar for both studies is the distinction between letters and non-letter shapes, however, their conclusions differ. Whereas Poirel, Pineau and Mellet (2008) predict a correlation of meaningfulness and GPE, we explain the distinction by different processing strategies for letters and non-letter shapes. These letter

processing strategies are different for children with reading disabilities (Fernandes et al., 2014; Lachmann, Steinbrink, Schumacher & van Leeuwen, 2009; Lachmann & van Leeuwen, 2007).

In the current study we investigate whether children with normal reading skills and children with poor reading abilities differ in the distinction of GPE for letters and non-letter shapes. We assume that the latter do not show a GPE for either kind of stimuli.

Hypothesis 6. *For children with normal reading skills the GPE appears for letters but not for non-letters. For children with poor reading abilities there is neither a GPE for letters nor for non-letters.*

Assuming that children with poor reading abilities are indeed familiar with the concept of letters as meaningful symbols, but are not able to use an automatized letter processing strategy properly, an absence of GPE for letters would indicate that the distinction of GPE for letters and non-letter shapes is caused by different processing strategies and not by meaningfulness.

6.2. Method

6.2.1. Participants

Seventy-one participants (36 female, $M_{age} = 9.7$ years; $SD_{age} = 0.5$ years) from the elementary schools Connewitz, Germany and Groenau, Germany (34 participants) and the Nikolaus-Obertreis Grundschule St.Wendel, Germany (37 participants) took part in this experiment. All participants reported normal hearing and normal or corrected to normal vision. The parents gave written consent for the children's participation. The study was approved by the ethical committee of the Faculty of Social Science of the University of Kaiserslautern. The permissions to conduct this study were obtained from the ministries of education, principals and teachers. The diagnostic procedure was conducted simultaneously for the whole class; the experimental session with 2–3 children simultaneously. Nine participants were excluded from further analysis because they did not finish the study

or because of external disturbance during their test session.

6.2.2. Diagnostic procedure

The cognitive abilities were diagnosed with the short form of the Grundintelligenztest Skala 2 Revision (CFT-20R, Weiß & Weiß, 2006). The CFT-20R delivers results as intelligence quotient (IQ, $M_{IQ} = 100$, $SD_{IQ} = 15$). To diagnose learning disabilities an $IQ_i < M_{IQ} - 2SD_{IQ}$ ($i =$ individual value) criterion was used. Since all children had an IQ higher than 70, no one had to be excluded.

The reading and writing abilities were diagnosed with the Salzburger Lesescreening (SLS 2-9, Wimmer & Mayringer, 2014) and additionally the Salzburger Lese- und Rechtschreibtest (SLRT-II, Moll & Landerl, 2014). In the SLS 2-9 reading abilities are given as reading quotient (LQ, $M_{LQ} = 100$, $SD_{LQ} = 15$). The SLRT-II checks reading and writing abilities with three subtests, one writing test, a word reading and a pseudo-word reading test. Results in all subtests are given as percent ranges.

To diagnose children with poor reading abilities first we used a $1SD$ criterion in the SLS, meaning that children with an LQ less than 85, were assigned to the group with poor reading abilities; this concerned 35 children. The results of the SLRT-II were not considered, because they gave no clear criterion to differentiate children with poor and normal reading skills, however, children diagnosed as having poor reading abilities in the SLS also showed poor performance in the SLRT-II word reading and pseudo-word reading test. This makes in sum 35 children assigned to the group with poor reading abilities and 36 children assigned to the group with normal reading abilities.

6.2.3. Material

Navon letters build-up of Latin letters (**a**, **e**, **u**), respectively Hebrew letters (**א**, **ש**, **ת**), as illustrated in Figure 6.1 were used in this study. To prevent influences of symmetry, all Latin letters were used as lowercase letters in italic style. The visual complexity of Latin letters and Hebrew letters was attempted to match as closely as possible.

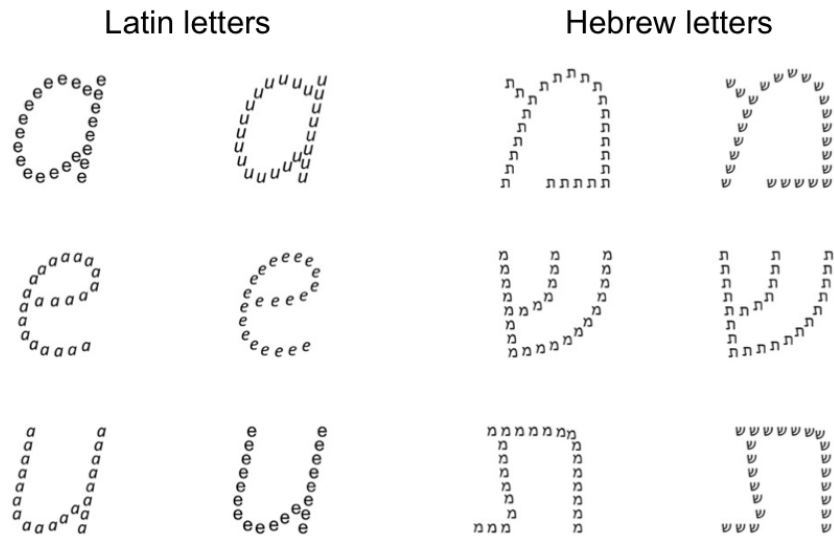


Figure 6.1.: The hierarchical, compound figures used in this experiment, build-up of Latin letters (left) or Hebrew letters (right). The letters on the local level differed from the letter on the global level.

The used stimuli were a combination of two different letters of the same scripture (e.g., an "a" build-up of "e"s or "u"s). Mixed stimuli (e.g., global Latin letters with local Hebrew letter or vice versa) and stimuli consisting of the same letter for the global and the local level (e.g., "a" build-up of "a"s) were not used.

Stimuli were presented using E-Prime 2.0 (Psychology Software Tools, Pittsburg, USA), controlled by a laptop computer running Microsoft Windows 7 in classrooms with dimmed light ratio. The stimuli were presented in black (0.4 cd/m^2) against a white background (28.9 cd/m^2), the global stimulus with a visual angle of approximately 8.5° , the local stimuli with a visual angle of approximately 1° . Target letters were presented with a visual angle of approximately 3° .

6.2.4. Procedure

The experimental session consisted of four blocks; two blocks with Latin letters and two blocks with Hebrew letters. In one block, using Latin letter stimuli or Hebrew letter stimuli, respectively, the participants were instructed to pay attention to the local level, while ignoring the global level. In the remaining two blocks (one with

Latin and one with Hebrew letter stimuli) participants had to pay attention to the global level and ignore the local level.

In each trial the participants had to decide whether or not the pre-designated target was on the specified level. Because of the used material three conditions were distinguished: the target could be at the *relevant level* to which the participants should pay attention to, at the *irrelevant level* which the participants should ignore or the target was *absent*, meaning that the target was neither at the local nor at the global level. Each block consisted of 180 trials (60 trials for each condition). The order of blocks and trials was randomized across participants.

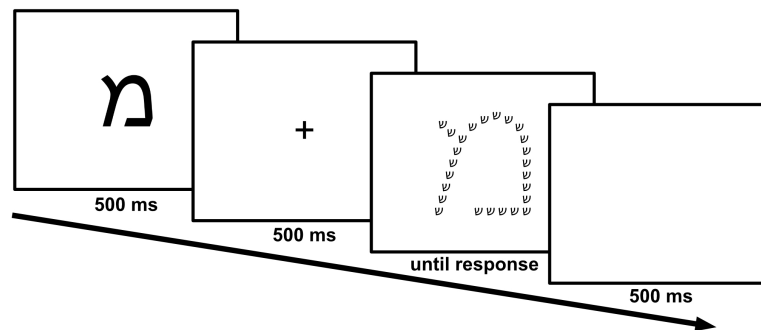


Figure 6.2.: Illustration of the single trials. Depending on the instruction, participants had to decide whether or not the pre-designated target was on the specified level.

Trials started with central presentation of a target letter for 500 ms, followed by a fixation cross in the center for another 500 ms. Afterwards, the Navon figure appeared until the participants responded or until the time-over criterion of 2000 ms, if no answer was given (see Figure 6.2). They responded by pressing the left respectively right button of the embedded laptop mouse using their left respectively right index finger. The usage for yes and no of the two buttons depended on the instruction and was counterbalanced between all participants. Reaction time and accuracy were recorded. Trials finished with a blank screen, presented for 500 ms. Before each block participants performed 18 practice trials (6 trials for each condition) giving them feedback about reaction time and accuracy.

6.3. Results

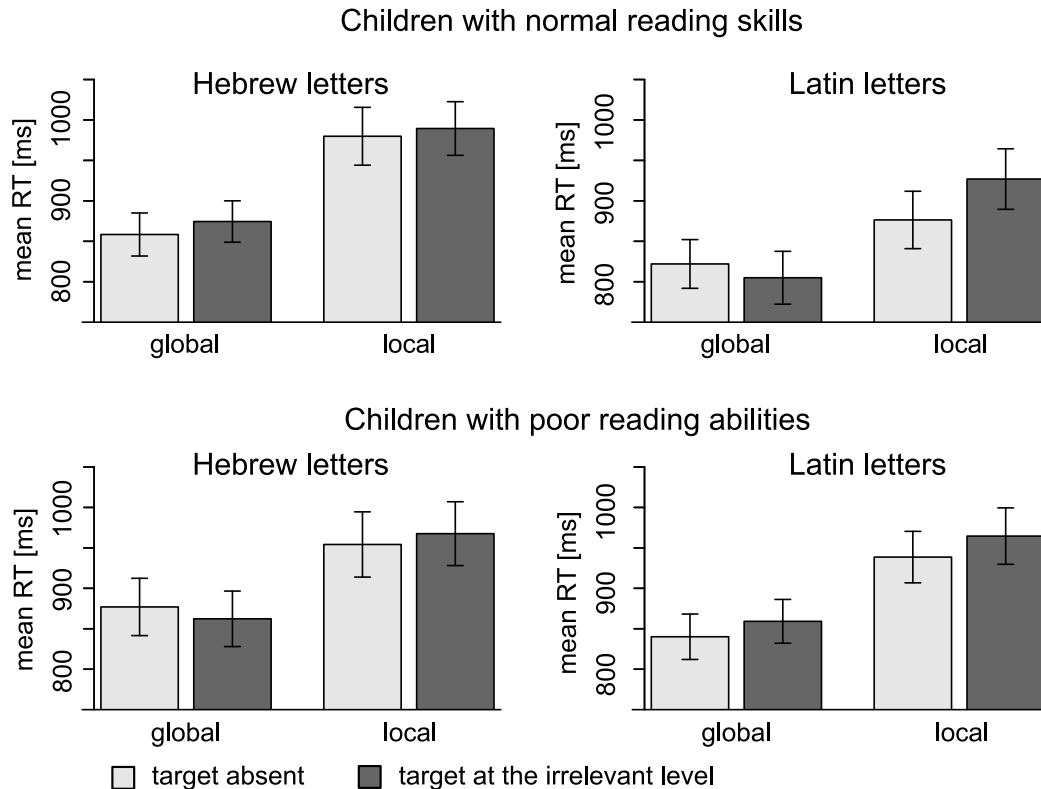


Figure 6.3.: Mean RTs in ms for children with normal reading skills (top) vs. children with poor reading abilities (bottom) in the *target absent* or *target at the irrelevant level* condition in global and local blocks, using Hebrew letters (left) or Latin letters (right)

The data from twelve participants were excluded because their overall accuracy was less than 70 %. For the remaining 49 participants (25 with poor reading abilities, 24 with normal reading skills) Error Rates (ER) and Reaction Times (RT) of correct responses within an individual outlier criterion of $150 \text{ ms} < RT < 2000 \text{ ms} \mid M_i + 3SD_i$ (i = individual value; 572 trials were excluded, 4 % of all trials) were analyzed. The overall mean RT was 883 ms ($SD = 127 \text{ ms}$) and ranged from 589 ms to 1204 ms; the overall mean ER was 14.6 % ($SD = 6.9 \%$) and ranged from 1.9 % to 28.2 %. Since there was no evidence for a speed-accuracy trade off $r(47) = .14, n.s.$, only the analysis of RT data is

reported.

The GPE predict an increase of RT for stimuli using the target as distractor at the level, which should get ignored. Because of theoretical based difference in target detection and non-detection, differences between conditions including the target at the specified level or the ignored level cannot be interpreted in this context. Therefore, further analyses only compare the two conditions (*target absent* and *target at irrelevant level*) in which target could not be detected at the specified level.

RT data were analyzed in a 2 x 2 x 2 x 2 ANOVA with *Material* (Latin letters or Hebrew Letters), *Level* (global or local), *Condition* ("target absent" or "target at irrelevant level") as within-participant factors and *Group* (children with poor reading abilities or controls) as between-participant factor. Mean RTs for the conditions are illustrated in Figure 6.3.

Main effects were observed for *Material*, $F(1, 47) = 10.37$, $p < .01$, $\eta_p^2 = .18$, with faster responses for Latin letters (880 ms) than for Hebrew letters (920 ms) and for *Level*, $F(1, 47) = 57.62$, $p < .001$, $\eta_p^2 = .55$, with faster reactions for the global level (850 ms) than for the local level (950 ms). A *Level* x *Condition* interaction, $F(1, 47) = 4.13$, $p < .05$, $\eta_p^2 = .08$, was observed, showing a larger congruency effect (larger mean RTs for "target at the irrelevant level" than for "target absent") on the local level compared to the global level.

6.3.1. Interactions with Group

A two-way interaction between *Material* and *Group*, $F(1, 47) = 4.43$, $p < .05$, $\eta_p^2 = .09$, showed that the difference in mean RTs for Latin letters and Hebrew letters is smaller for children with poor reading abilities (14 ms) than for children with normal reading skills (68 ms). The four-way interaction *Material* x *Level* x *Condition* x *Group*, $F(1, 47) = 5.24$, $p < .05$, $\eta_p^2 = .10$, reflects that groups differ in the strength of interference effects at the different levels for Latin and Hebrew letter stimuli.

Due to these interactions we calculated 2 x 2 x 2 ANOVAs with the factors *Material*, *Level* and *Condition* for each group separately.

6.3.2. Children with normal reading skills

For the children with normal reading skills there were main effects for *Material*, $F(1, 23) = 14.81$, $p < .001$, $\eta_p^2 = .39$, with faster reactions for Latin letters (858 ms) than for Hebrew letters (926 ms) and for *Level*, $F(1, 23) = 33.37$, $p < .001$, $\eta_p^2 = .59$, with faster reactions for the global level (840 ms) than for the local level (943 ms). A two-way interaction between *Level* and *Condition*, $F(1, 23) = 5.72$, $p < .05$, $\eta_p^2 = .10$, was observed, showing that the interference effect from distractors at the ignored level was larger when attending the local level (30 ms) than to the global level (0 ms). The additional three-way interaction *Level* x *Condition* x *Material*, $F(1, 23) = 6.47$, $p < .05$, $\eta_p^2 = .22$, showed, that this asymmetric interference effect differs between Latin letters and Hebrew letters, and allowed us to analyse the data for Latin and Hebrew letters separately.

For Latin letters the participants responded faster for the global level (813 ms) than for the local level (902 ms), $F(1, 23) = 11.63$, $p < .01$, $\eta_p^2 = .34$ (*global advantage effect*). We obtained an interaction between *Level* and *Condition*, $F(1, 23) = 15.46$, $p < .001$, $\eta_p^2 = .40$, with an interference from distractors at the global level when participants attend to the local level, $t(23) = 2.76$, $p < .05$, but not vice versa, $t(23) = 1.00$, $p = .29$ (*asymmetric interference effect*).

For Hebrew letters there was only an effect for *Level*, $F(1, 23) = 16.94$, $p < .001$, $\eta_p^2 = .42$, with faster responses to the global level (866 ms) compared to the local level (985 ms). Neither differences between the conditions, $F(1, 23) = 1.37$, $p = .25$, $\eta_p^2 = .06$, nor an interaction between *Level* and *Condition*, $F(1, 23) < 1$, could be observed.

6.3.3. Children with poor reading abilities

For children with poor reading abilities we observed only one main effect for *Level*, $F(1, 24) = 25.20$, $p < .001$, $\eta_p^2 = .51$, showing that reactions for the global level (860 ms) were faster compared to the local level (956 ms). This group showed neither significant differences between Latin letters (901 ms) and Hebrew letters (915 ms), $F(1, 24) < 1$, nor any further interactions.

6.4. Discussion

The aim of this study was to figure out, whether letters and non-letters in hierarchical, compound figures are processed differently in children with normal reading skills versus children with poor reading abilities. On the one hand, this would transfer findings from prior studies, showing that there is a distinction in letter processing between children with normal reading skills and children with poor reading abilities (Fernandes et al., 2014; Lachmann, Steinbrink et al., 2009; Lachmann & van Leeuwen, 2007), to paradigms using Navon figures. On the other hand, this would give us information about the underlying mechanisms which cause - or better activate - these processing strategies.

For children with normal reading skills the results replicate earlier studies (Beaucousin et al., 2011; Poirel, Pineau & Mellet, 2008). For well-known Latin letters we could observe the GPE, strictly speaking, the two components of GPE; the *global advantage* and the *asymmetric interference*. Responses given to the global level were faster than responses to the local level, and there were faster RTs for the local level if the target was not given as distractor at the global level.

For the unknown Hebrew letters, we could only observe faster responses for the global level than for the local level, but no interferences, meaning that for Hebrew letters there was a *global advantage* but **no** *asymmetric interference* and therefore no GPE in its complete form.

For children with poor reading abilities different results were observed. Neither for Latin nor for Hebrew letters they showed a GPE. For each material we could observe a *global advantage* but *no interference*. Moreover, they did not show a distinction in mean RTs for Latin letters and Hebrew letters. These two facts, the missing of GPE for Latin letters and comparable RTs for Latin and Hebrew letters, suggest that children with reading disabilities, in contrast to children with normal reading skills, use the same processing strategies for letters as well as for unknown patterns. This is in accordance to prior studies. For example regarding symmetry effects (e.g., Lachmann & van Leeuwen, 2007), the lack of symmetry suppression for letters in children with development dyslexia leads to faster responses for letters with a symmetry axis compared to asymmetrical letters in a same-different task. For children with normal reading skills this benefit of symmetry is only observed

for non-letter shapes (e.g., dot patterns). In paradigms using contextual embedded figures (e.g., letters surrounded by geometrical shapes) as used by Fernandes et al. (2014) and Lachmann and van Leeuwen (2008a) children diagnosed with developmental dyslexia benefit from congruent (i.e., the surrounding shape has the same geometry as the embedded letter) compared to incongruent (i.e., the surrounding shape has another geometry as the embedded letter) surroundings. This difference in congruency for letters was not observed in adults or children with normal reading skills.

The fact that the children with reading disabilities are able to read, even though at a worse level, indicates that they are in principle familiar with the letter concept as meaningful symbols. Thus, if meaningfulness of the used stimuli is the key factor for the appearance of the GPE, as predicted by Poirel, Pineau and Mellet (2008), also children with poor reading abilities should show a GPE for Navon figures build-up of meaningful letters. Since, in our study, the group with poor reading abilities did not show a GPE for letter stimuli, we conclude, that not just meaningfulness alone is crucial for the appearance of GPE. According to prior studies (e.g., Fernandes et al., 2014; Lachmann, Steinbrink et al., 2009; Lachmann & van Leeuwen, 2007; Rusiak, Lachmann, Jaskowski & van Leeuwen, 2007), there is a lack of automatized specific letter processing strategies in children with reading disabilities. This finding could explain, why children with poor reading abilities in our experiment did not show a distinction between letters and non-letters, whereas for children with normal reading skills, which use different processing strategies for letters and non-letters, we could observe a distinction in GPE. This supports our hypothesis in Study 1, that the distinction in GPE for letters and non-letter shapes in children with normal reading skills is caused by different processing strategies and not just by meaningfulness of stimuli.

It is not our aim to completely contradict the conclusion of Poirel, Pineau and Mellet (2008), explaining that appearance of GPE for letter stimuli is caused by meaningfulness, because their study demonstrate that the GPE also appears for meaningful non-letter objects, i.e. pictograms of real objects (e.g., an umbrella or a flower). The letter-specific processing strategy is not an innate strategy, it is developed during reading acquisition (Lachmann & van Leeuwen, 2014). According to Dehaene and Cohen (2007) this strategy is a result of modification of earlier

developed object recognition strategies. Prior studies demonstrate, that letters are connected with auditory information in a cross-modal usage (Blau et al., 2010; Blomert, 2011; Froyen, Van Atteveldt, Bonte & Blomert, 2008). Thus, the usage of the analytic letter processing strategy is connected with auditory information, too. As a consequence, if auditory information – or in other words ”meaning” – activates usage of these strategies they also should be activated for other meaningful material.

Therefore, the apparent contradiction between the results of Poirel, Pineau and Mellet (2008) and our results in Study 1 and 2 could be resolved by a reinterpretation of causality in Poirel’s paradigm.

The distinction in GPE between letters and non-letters is not caused just by meaning, it is caused by different processing strategies which again are triggered by meaning, i.e. auditory information, leading to a transfer of letter-specific processing strategies to other meaningful objects.

7. Study 4: Serial position effects in mixed letter/non-letter strings

7.1. Aim of the study

In the previous studies we showed differences between letter and non-letter processing and investigated some aspects which influence these differences.

In Study 1 we demonstrated that reading-like conditions benefit the appearance of letter and non-letter distinction in processing hierarchical embedded figures. Together with our results of Study 2 and 3 we predict, that this distinction is not just caused by familiarity or the meaningfulness of the stimuli. The results suggest letter-specific processing strategies, which are described as analytic in contrast to more holistic strategies for non-letter shapes. Thereby, we explained, that these holistic strategies for non-letters differ from what we called holistic in the case of whole word reading. Holistic whole word reading is not just the recognition of words as a whole structure, but include the processing of the smaller units (i.e., graphemes, morphemes, rhymes and syllables) which form those words. Hence, the "holistic" whole word reading also includes analytic processes. This interaction between word level and sub-levels could explain the results of Study 1 and 2, in which we assumed that the global level of our Navon figures mimics the word level in fluent reading.

For whole word reading this parallel processing is described in dual-route models of reading (Coltheart, 2007; Coltheart et al., 2001; Grainger & Ziegler, 2011). Thereby, the analytic component of whole word processing is integrated in the non-lexical route, in which phonological information is required in a sequential grapheme-to-phoneme decoding. The holistic processing reflects the reading strategy on the lexical route, in which the pronunciation of the whole word is

retrieved from a mental dictionary, based on some salient visual cues.

However, these models relate to normal reading and can not explain why this parallel processing also should appear for paradigms using letters but not words. Although we assumed that the visual angles of the global level of our Navon figures were close to those of words in fluent reading, they are evidently no words. For studies using single letters (e.g., Fernandes et al., 2014; Hermens, Lachmann & van Leeuwen, 2013; Lachmann & van Leeuwen, 2008a, 2008b) it is obvious, that the letter-specific processing strategy is triggered by the usage of letters. But this cannot explain why we should obtain strategies which are typical for whole word reading, in paradigms using compound letter stimuli. Study 1 and 2 suggest, that the usage of letters in Navon figures triggers automatically a holistic processing of the global level, which is very similar to the holistic processing of words in whole word reading. This would mean, that letter configurations not only activate letter-specific processing strategies, but also a holistic whole word reading strategy, and that words are not necessary to activate this holistic strategy for extended letter structures. However, since Navon figures are evidently no words, we cannot say this for sure.

In this study we would like to explore, what triggers the appearance of the holistic whole word strategy. Is this strategy activated automatically by letters or by words?

In a paradigm using hierarchical structures, which are more similar to words than Navon figures, Mason (1982) demonstrated different serial-position effects for letter, digits and symbol strings. In a target detection task, participants gave faster responses for more central positions in a five-character symbol string compared to the terminal positions, resulting in a U-shaped function for reaction times depending in the different positions in the string. For letter strings, they observed an M-shaped function, showing faster responses for the first, central and fifth position compared to the neighboring positions. Hammond and Green (1982, p. 67) concluded in their study: "this result is not restricted to any one non-letter character set, nor is visual familiarity or nameability crucial".

The observation of reaction time advantage for the initial and final positions in letter strings seems to be a hint on the reading strategy, which is typical for the *partial alphabetic phase* of reading acquisition (Ehri, 1995). During this phase

the initial and final letters of a word play an important role in whole word recognition, although the understanding of letter-sound relation is not fully developed. The results of Mason (1982) and Hammond and Green (1982) were replicated in different studies, which additionally use modified paradigms to examine also the influence of the *length and crowding* of the string (Grainger et al., 2010), the *fixation position* (Tydgat & Grainger, 2009) and the *eccentricity from the focal point of view* (Chanceaux & Grainger, 2012), the *frequency of specific letters* in written real words (Pitchford et al., 2008) and the *reading ability* (Ziegler, Pech-Georgel, Dufau & Grainger, 2010). It should be noted, that depending on the paradigm, only the advantage for the initial position could be observed (e.g., Tydgat & Grainger, 2009).

Since most studies used strings, which either were completely composed of letters *or* were completely composed of non-letters, it is not clear whether this appearance of a whole word reading strategy is caused by the target (i.e., a single letter) or by the stimulus, which is combined of different letters similar to a real word. Tydgat and Grainger (2009) tried to answer this question in a modified paradigm. They used stimuli, which included a single letter in a string of symbols (e.g., L\$%&@) or a single symbol in a letter string (e.g., LS&TD). If this whole word reading strategy was triggered only on presentation of a the letter-string, meaning the stimulus is similar to a word, it should not appear when the letter target was embedded in a symbol-string. Likewise, if the symbol was embedded in a letter string, the advantage for the initial position should also appear, when participants were advised to detect a symbol. The results showed neither an advantage of the initial position for symbols in a letter-string nor a lack of this advantage for letters, when they were embedded in a symbol-string. This finding suggests, that the whole word reading strategy was not triggered by the string but by the nature of target. In other words, the word level had no influence on the chosen strategy; it only depended whether the participants were advised to detect a letter or a symbol.

Unfortunately, we can not exclude completely an influence of the "word level". The participants knew, that in this paradigm, the letter was embedded in a non-letter sting and vice versa. Considering this knowledge, it is possible that the strategies were switched and the reading strategy was automatically triggered

by a string of non-letters.

In the following experiment, therefore, we tried to rule out this possibility by using strings which are randomly combined of letters **and** non-letters, or exactly, letters from the Cyrillic and Hebrew alphabet, which were similar in their visual features. Thus, the strings definitely could not influence the chosen strategy. Thereby, we ensure whether the target (i.e., letter vs. non-letter) or the string triggers the appearance of different strategies. If the word level (i.e., the string) triggers the strategy, we should observe the same pattern of reaction times for the letter targets as well as for the non-letter targets. If the strategy is caused by the target, we should observe different serial-position functions; according to prior studies using these kind of stimuli a U-shaped function for non-letter targets and a linear or more M-shaped function for letter targets. Prior studies showed that for transparent orthographies the linear trend is more dominant than the end-facilitation at the last position (Ktori & Pitchford, 2009). Hence, we expect to find the linear function instead of the M-shaped one, because our participants are more familiar with the transparent German orthography.

Hypothesis 7. *For Latin letter targets reaction times and error rates differ for the different positions in a mixed five-character string, with increasing reaction times from the left to the right terminal position in the character-string.*

Hypothesis 8. *For Hebrew and Cyrillic letter targets reaction times and error rates differ for the different positions in a mixed five-character string, with increasing reaction times from the central position to the terminal positions in the character-string, describing a U-shaped position function.*

7.2. Method

7.2.1. Participants

Forty-one students from the University of Kaiserslautern (Germany), were payed or received course credit for their participation. All participants were right handed, German native speakers with normal or corrected to normal vision. They gave written consents for participation in this study. The study was approved by the ethical committee of the Faculty of Social Science of the University of Kaiserslautern.

7.2.2. Material

Stimuli were combinations of five different characters, forming a string. The characters were randomly chosen from 12 possible characters, containing four Latin letters, four Hebrew letters and four Cyrillic letters. All letters were self-drawn and partially abstracted to match their visual features as closely as possible. The used material and an example of the character strings are shown in Figure 7.1. The stimuli were presented in black (0.4 cd/m²) against a white background (28.9 cd/m²). Each single character was presented with a visual angle of approximately 0.5° x 0.5°, combined to a five-character strings with a visual angle of approximately 3° in width.

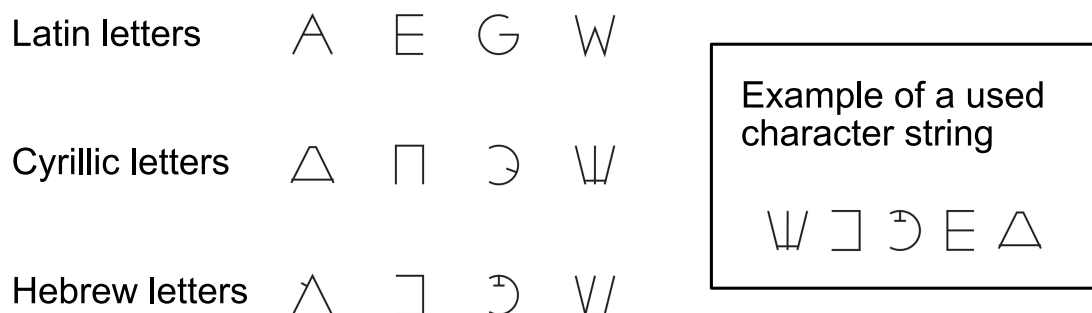


Figure 7.1.: Illustration of the used stimuli. Character strings (right side) were randomly composed of five different characters from the three letter groups (Latin letter, Cyrillic letters and Hebrew letters; left side)

The experiment run on a PC with Windows 7 using E-Prime 2.0 (Psychology Software Tools, Pittsburg, USA) and took place in a test cubicle with sound attenuation and controlled lighting. There was no fixation of the head.

7.2.3. Procedure

The experiment consisted of 480 trials spread over two sessions. Between the sessions participants could choose if they like to take a short break. In a target-detection-task, participants had to decide whether or not a pre-designated target was part of the presented character string. Participants responded by pressing "s" or "l" on the keyboard. For example, they pressed "s" with their left index finger if they thought the target character is part of the stimulus or "l" with their right index finger if they had the opposite opinion. The assignment of keys and response alternatives was counterbalanced between participants.

Each character appeared 40 trials as target. In half of these trials, the target was absent, meaning the target letter was not part of the character-string. The remaining 20 trials were counterbalanced in a way that the target was present for four times on each position of the five-character string. In sum, each kind of letters (Latin, Hebrew, Cyrillic) was shown 16 times on each position.

Trials began with the presentation of the target character in the center of the screen for 1000 ms, followed by a blank screen for 500 ms. The stimuli were shown centrally, until the participants responded. After a blank screen, shown for 1500 ms, the next trial began. Participants completed 30 training trials, giving feedback for 1000 ms about their individual reaction times and accuracy.

7.2.4. Results

Two participants were excluded from further analysis, because of an accuracy less than 70%. For the remaining 40 participants error rates (ER) and mean reaction times (RT) of correct responses within a range 150 ms and 2000 ms (95 trials excluded, 0.5 %) were analyzed. The overall mean ER was 11.5 % ($SD = 6.9$ %) and ranged from 0.2 % to 28.2 %. The overall mean RT was 633 ms ($SD = 127$ ms) and ranged from 414 ms to 1038 ms. Since there was a speed-accuracy trade off, $r(37) = .53$, $p < .001$, RT as well as ER data were analyzed in repeated measures

3 x 5 ANOVAs with the factors *Material* (Hebrew letters, Cyrillic letters, Latin letters) and *Position* (1-5 from left to right in the character-string).

7.2.5. Results of RT Analysis

We observed main effects for *Material*, $F(2, 76) = 36.77$, $p < .001$, $\eta_p^2 = .49$ as well as for *Position*, $F(4, 152) = 33.46$, $p < .001$, $\eta_p^2 = .47$, and a *Material* x *Position* interaction, $F(8, 304) = 8.11$, $p < .001$, $\eta_p^2 = .18$. To figure out differences between the letter groups, we compared these groups pairwise in post-hoc ANOVAs. Results are summarized in Table 7.1.

	Hebrew vs. Cyrillic	Latin vs. Hebrew	Latin vs. Cyrillic
Material	$F(1, 38) = 67.94$, $p = .110$, $\eta_p^2 = .07$	$F(1, 38) = 43.53$, $p < .001$, $\eta_p^2 = .53$	$F(1, 38) = 38.72$, $p < .001$, $\eta_p^2 = .50$
Position	$F(4, 152) = 36.69$, $p < .001$, $\eta_p^2 = .49$	$F(4, 152) = 19.33$, $p < .001$, $\eta_p^2 = .34$	$F(4, 152) = 26.84$, $p < .001$, $\eta_p^2 = .41$
Material x Position	$F(4, 152) = 1.84$, $p = .125$, $\eta_p^2 = .05$	$F(4, 152) = 8.64$, $p < .001$, $\eta_p^2 = .19$	$F(4, 152) = 14.11$, $p < .001$, $\eta_p^2 = .27$

Table 7.1.: Results from post-hoc ANOVAs of mean RT pairwise for letter groups.

As shown in Table 7.1, the post-hoc ANOVA for Hebrew versus Cyrillic did show neither a main effect for *Material* nor an interaction between *Position* and *Material*, whereas the ANOVA for Latin versus Hebrew and Latin versus Cyrillic showed both, a main effect for *Material* and a *Material* x *Position* interaction. Since there were no differences between Hebrew letters and Cyrillic letters, these factor levels were merged to one factor level, called *shape*, in all further analyses.

Considering this new factor level the 2 (letters vs. shapes) x 5 (position 1-5) ANOVA showed following results:

Again, there were main effects for *Material*, $F(1, 38) = 44.37$, $p < .001$, $\eta_p^2 = .53$, with faster responses for letters (575 ms) than for shapes (632 ms) and *Position*, $F(4, 152) = 28.03$, $p < .001$, $\eta_p^2 = .42$, showing that responses are faster for the center position (Position 3, 564 ms) and become slower the further they are

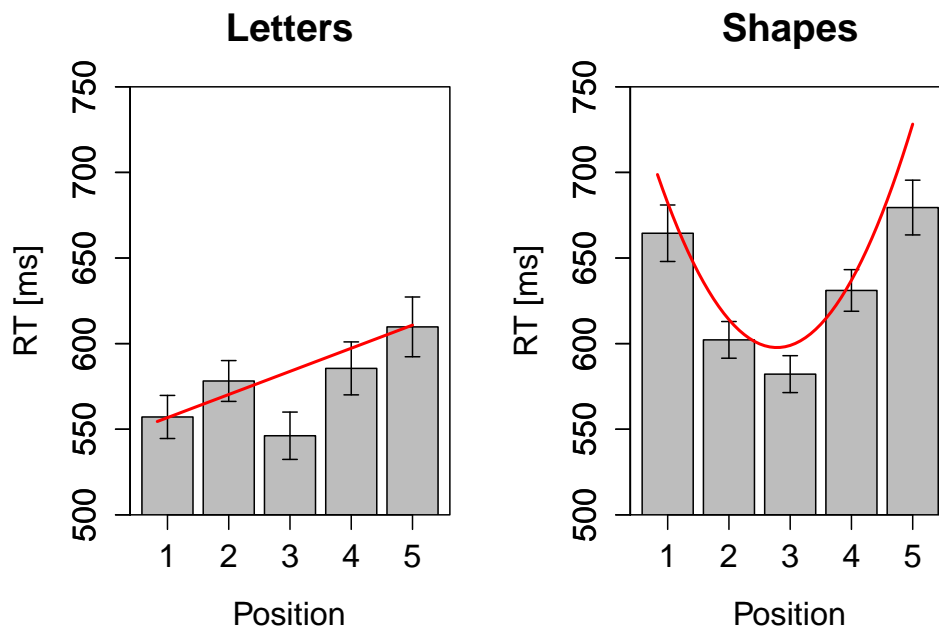


Figure 7.2.: Mean RTs for positions in letters (left) and shapes (right). The red lines illustrate the best fitting functions (RT_{L2} and RT_{S2}) without considering the central position.

away from the central position (Position 2: 590 ms, Position 4: 608 ms, Position 1: 611 ms and Position 5: 642 ms). Also the *Material* \times *Position* interaction, $F(4, 152) = 15.31, p < .001, \eta_p^2 = .29$, was still observed.

To explore this interaction, we conducted 2 \times 2 ANOVAs, with the factors *Material* (letters vs. shapes) and *Position*, with pairwise comparison for the positions in the string (e.g., Position 1 vs. Position 2, Position 1 vs. Position 3, etc.). Since we were only interested in *Material* \times *Position* interactions, further analyses only report interactions and no main effects. Interactions and results of post-hoc Bonferroni corrected t-tests are shown in Table 7.2.

As shown in Table 7.2, all interactions considering the first position were significant, mostly caused by differences in performance of letters and non-letters at the first position in strings. Tendencies of RTs across the positions in the strings can be seen in Figure 7.2. For shapes, the mean RTs described a U-shape with slow responses for the first position (664 ms), fastest responses for the central po-

Material x Position interaction	t-test for Position in letter strings	t-test for Position in shape strings
Position 1 vs. Position 2 $F(1, 38) = 55.30, p < .001, \eta_p^2 = .59$	$t(38) = 3.04, p = .004^*$	$t(38) = 6.44, p < .001^*$
Position 1 vs. Position 3 $F(1, 38) = 48.69, p < .001, \eta_p^2 = .56$	$t(38) = 1.17, p = .249$	$t(38) = 7.30, p < .001^*$
Position 1 vs. Position 4 $F(1, 38) = 23.89, p < .001, \eta_p^2 = .38$	$t(38) = 2.24, p = .031$	$t(38) = 3.40, p = .002^*$
Position 1 vs. Position 5 $F(1, 38) = 10.52, p < .01, \eta_p^2 = .22$	$t(38) = 4.36, p < .001^*$	$t(38) = 1.52, p = .136$
Position 2 vs. Position 3 $F(1, 38) = 1.21, p = .28, \eta_p^2 = .03$		
Position 2 vs. Position 4 $F(1, 38) = 2.52, p = .12, \eta_p^2 = .06$		
Position 2 vs. Position 5 $F(1, 38) = 13.87, p < .001, \eta_p^2 = .27$	$t(38) = 2.89, p = .006$	$t(38) = 7.61, p < .001^*$
Position 3 vs. Position 4 $F(1, 38) < 1, p = .47, \eta_p^2 = .01$		
Position 3 vs. Position 5 $F(1, 38) = 10.14, p < .01, \eta_p^2 = .21$	$t(38) = 5.76, p < .001^*$	$t(38) = 9.08, p < .001^*$
Position 4 vs. Position 5 $F(1, 38) = 3.61, p = .07, \eta_p^2 = .09$		

Table 7.2.: Interactions and results of post-hoc t-tests (*significant for Bonferroni adjusted α -level of .005).

sition (Position 3, 582 ms) and again slow responses for the last position (Position 5, 679 ms). For letters, there was no such U-shaped function, resulting from fast RTs at the first position (557 ms), which did not differ significant from RTs at the central position (Position 3, 546 ms). However, for letters slowest responses were observed at the right terminal position (Position 5, 610 ms) of the string, too.

To examine the best fitting serial position function, we performed a trend analysis. Considering all positions, results showed a significant linear effect, $F(1, 38) = 13.14, p < .001$, as well as a quadratic effect, $F(1, 116) = 9.37, p < .01$, for letters, explaining 86.0 % of variance. For shapes, there was also a linear effect, $F(1, 38) = 6.86, p < .05$, as well as a quadratic effect, $F(1, 116) = 138.91$,

$p < .001$, which explain 91.5 % of variance.

The resulting serial position functions are as follows:

$$\text{for letters: } RT_{L1} = 564.2 - 11.3 \cdot (pos - 3) + 5.6 \cdot (pos - 3)^2$$

$$\text{for shapes: } RT_{S1} = 590.4 - 5.9 \cdot (pos - 3) + 20.4 \cdot (pos - 3)^2$$

The term $(pos - 3)$ is used to adjust the serial position function centrally to Position 3, where the fastest mean RT was observed. As can be seen from the two functions above, the quadratic term has a much larger influence on RTs for shapes as for letters, resulting in the U-shape, which can be seen in Figure 7.2.

To exclude the RT advantage on Position 3 caused by fixation at this position, while the stimuli appeared, we modeled further serial position functions without considering Position 3. This procedure results in the following serial position functions, as best fitting models.

$$\text{for letters: } RT_{L2} = 582.7 - 11.3 \cdot (pos - 3)$$

$$\text{for shapes: } RT_{S2} = 598.2 - 5.9 \cdot (pos - 3) + 18.5 \cdot (pos - 3)^2$$

Results showed a significant linear effect, $F(1, 38) = 13.14$, $p < .001$, for letters, explaining 88.2 % of variance. An expanded model, including an additional squared term did not show a significant improvement, $\chi^2_{diff}(1) = .07$, $p = .80$, showing that after excluding the advantage, caused by fixation, RTs in letter strings only show a linear serial position effect.

For shapes, there was still a linear effect, $F(1, 38) = 6.9$, $p < .05$, as well as a quadratic effect, $F(1, 77) = 71.17$, $p < .001$, which explains 91.7 % of variance.

Results of error rate analysis

Analysis of arcsin square-root transformed ERs showed similar results to that of mean RTs. Mean ERs for different positions and material are illustrated in Figure 7.3. Main effects were observed for *Material*, $F(2, 76) = 21.97$, $p < .001$, $\eta_p^2 = .36$, and for *Position*, $F(4, 152) = 8.68$, $p < .001$, $\eta_p^2 = .19$, and a *Material* x *Position* interaction, $F(8, 304) = 3.74$, $p < .001$, $\eta_p^2 = .10$. Post-hoc ANOVAs, comparing the letter groups pairwise, showed *Material* x *Position* interactions for

Latin vs. Hebrew, $F(4, 152) = 3.20$, $p < .05$, $\eta_p^2 = .08$, and for Latin vs. Cyrillic, $F(4, 152) = 7.34$, $p < .001$, $\eta_p^2 = .16$. Since, for Hebrew vs. Cyrillic there was no interaction $F(4, 152) = 1.34$, $p = .26$, $\eta_p^2 = .03$, these factor levels again were merged into one factor level *shape* in any further analyses. The 2 (letter vs. shapes) x 5 (position 1-5) ANOVA, showed following results.

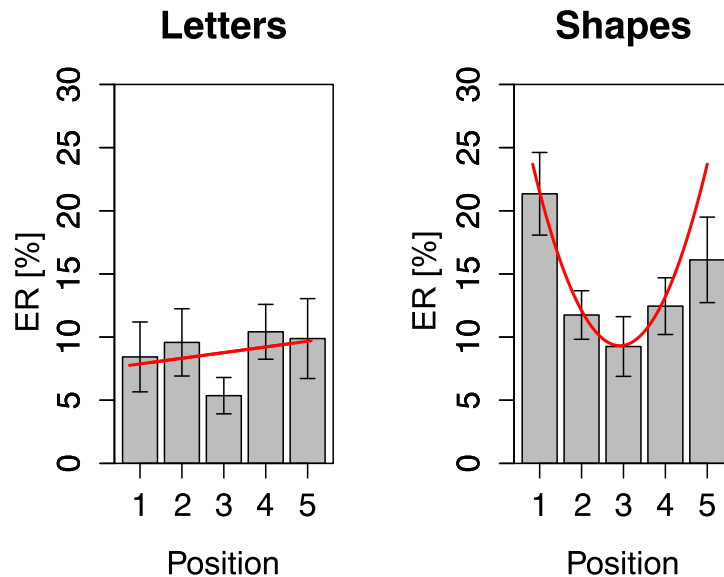


Figure 7.3.: Mean ER for positions in letters (left) and shapes (right). The red line illustrate the best fitting function (ACC_L and ACC_S).

Again, there were main effects for *Material*, $F(1, 38) = 55.78$, $p < .001$, $\eta_p^2 = .59$, with less errors for letters (8.7 %) than for shapes (14.2 %), and *Position*, $F(4, 152) = 5.57$, $p < .001$, $\eta_p^2 = .13$, showing a low ER for the center position (Position 3, 92.7 %), and increasing ER for positions that are further away from the central position (Position 2: 10.7 %, Position 4: 11.4 %, Position 1: 14.9 % and Position 5: 13.0 %). Also the *Material* x *Position* interaction, $F(4, 152) = 6.01$, $p < .001$, $\eta_p^2 = .14$, was still observed. Because of this interaction we analyzed letters and shapes separately.

For letters ERs did not differ significantly for *Position*, $F(4, 152) = 1.87$, $p = .118$, $\eta_p^2 = .05$, although the mean ER at the fixation point (Position 3, 5.3 %) was a bit lower compared to the mean ERs at the other positions (Position 1:

8.4 %, Position 2: 9.5 %, Position 4: 10.4 %, Position 5: 9.9 %).

For shapes there was an effect for *Position*, $F(4, 152) = 12.32$, $p < .001$, $\eta_p^2 = .24$, hence, the differences of mean ERs for positions in the shape-string were compared in pairwise Bonferroni corrected t-test (see Table 7.3).

Position i vs. j	Differences in means of ER (Position $i-j$)	t-test for Position $i-j$
Position 1 vs. 2	9.6 %	$t(38) = 5.72$, $p < .001^*$
Position 1 vs. 3	12.1 %	$t(38) = 5.50$, $p < .001^*$
Position 1 vs. 4	8.9 %	$t(38) = 3.89$, $p < .001^*$
Position 1 vs. 5	5.2 %	$t(38) = 2.22$, $p = .03$
Position 2 vs. 3	2.5 %	$t(38) = 1.69$, $p = .10$
Position 2 vs. 4	- 0.7 %	$t(38) < 1$, $p = .64$
Position 2 vs. 5	- 4.4 %	$t(38) = 2.11$, $p = .04$
Position 3 vs. 4	- 3.2 %	$t(38) = 2.37$, $p = .02$
Position 3 vs. 5	- 6.9 %	$t(38) = 3.20$, $p < .003^*$
Position 4 vs. 5	- 3.7 %	$t(38) = 1.90$, $p = 0.07$

Table 7.3.: Results from pairwise t-tests of ERs for positions in the shape strings (*significant for Bonferroni adjusted α -level of .005).

As shown in Table 7.3, the mean ER at Position 1 (21.3 %) was significant higher compared to all other positions and additionally the mean ER at Position 5 (16.1%) was significant higher compared to the center position (Position 3, 9.3 %). Although results of the remaining positions (Position 2: 11.8 % and Position 4: 12.5%) do not differ significantly from the central position, they suggest, that for shapes also the mean ERs described a U-shape. Again, we performed trend analysis, to explore the best fitting functions.

The best serial position function for shapes, $ER_S = 9.5 + 2.3 \cdot (pos - 3)^2$ shows a significant quadratic effect, $F(1, 38) = 49.78$, $p < .001$, and explains 54.1 % of variance. An expanded model including an additional linear term did not show a significant improvement, $\chi^2_{diff}(1) = 3.08$, $p = .08$.

For letters, the best serial position function, $ER_L = 8.7 + 0.4 \cdot (pos - 3)$, showed a slight but not significant linear effect. However, the linear model shows a significant improvement, compared to a baseline model, which only assumes random intercepts caused by participants, $\chi^2_{diff}(3) = 10.89$, $p < .05$.

7.3. Discussion

We investigated the connection between the analytic letter processing strategy and the holistic whole word reading strategy in letter strings. The aim was to replicate results from prior studies, demonstrating that the holistic strategy for letter-strings differs from that for non-letter-strings. By using strings which were randomly compound of Latin letters, Hebrew letters and Cyrillic letters, we determined whether these different processing strategies are triggered by the string or by the target letter respectively non-letter. Thereby, we expected that a typical word reading strategy would be triggered automatically, if the participants were instructed to detect a Latin letter target. This reading strategy would result in increasing RTs from the left end of the string, to the right end. Since the participants were not familiar with reading Hebrew or Cyrillic, this reading strategy should not be triggered, if participants were instructed to detect a target out of these alphabets. Instead of a linear increase from left to right, participants should show a symmetrical increase in RTs with fastest responses for the central position and slowest responses for the initial and final positions.

The results supported our hypotheses. For RTs, a linear model could explain 88.2 % of variance for Latin letters; for Hebrew and Cyrillic letters a symmetrical U-shaped function, explaining 91.7 % of variance, was extracted. Similar position functions could be observed for ERs. Since for all conditions the strings were blend out of Latin letters as well as Hebrew letters and Cyrillic letters the distinction could not be caused by the string. The distinction could only result from the nature of the target letter, suggesting that the pre-designated target letter triggers the used target searching strategy. Hence, if participants were instructed to detect a Latin letter in the string, a typical reading strategy was activated.

This idea, that the appearance of reading or letter-specific processing strategies is triggered by the knowledge of which kind of material should be processed, is in accordance with prior studies. For examples, task using contextual embedded figures (e.g., surrounded letters and non-letter shapes) show different effects, depending whether participants should make a categorial decision (letter or non-letter) or whether participants should decide in a same-different task whether two shown shapes, either letters or non-letters, are the same (van Leeuwen & Lachmann,

2004). This finding supports our hypothesis that prior knowledge about the target influences the participants' strategy.

One question, that should be answered by the prior studies (Studies 1 - 3) was, whether distinctions between letters and non-letters, which could be observed in different paradigms, are caused by familiarity, meaning or differences in the underlying processing strategies. The results of those prior studies support the hypotheses of an analytic letter processing strategy versus a holistic object recognition strategy for non-letters. The results of the current study, showing that the appearance of letters not just seems to trigger automatically a specific letter processing strategy but also a specific whole word reading strategy, reinforce this idea and form an extension to the level of word reading.

Theories of reading acquisition assume different phases, in which each phase is build on the previous phases, rather than just replacing those (Ehri, 1995; Frith, 1986). Actually, also in skilled readers, strategies, which are developed in an earlier stages of reading acquisition, could be observed. Following the functional coordination theory (Lachmann et al., 2014, for a review), reading beginners have to learn consciously how to use these strategies, whereas in advanced readers these strategies become more and more automatized, but still are processed in parallel. Dual-route models of reading explain, how the different strategies are benefited, depending on the requirements of the task (Coltheart, 2007; Grainger & Ziegler, 2011).

Therefore, in paradigms using single letters, participants could automatically use an analytical letter processing strategy, which is developed during earlier phases of reading acquisition. Other studies, exploring whole word reading, could demonstrate a holistic whole word reading strategy which is developed during later phases of reading acquisition. The current study, seems to give an example of the reading strategy which is developed during a middle phase of reading acquisition; according to Ehri (1995) somewhere between the partial alphabetic phase, in which the initial and final letters are more important for word recognition, and the full alphabetic phase, in which readers are able to transform unfamiliar spellings of words into blended pronunciation. During this stage, an alphabetic word reading strategy is used (see Frith, 1985), meaning a grapheme-by-grapheme decoding of written words. This could be observed in beginning readers (e.g., children in the

elementary school), which are familiar with the concept of graphemes, naming letter-sound relation, but cannot profit from orthographic skills (Frith, 1985) and a highly developed lexical route (see Coltheart, 2007). They read a word, by pronouncing the graphemes step by step, beginning from the initial letter (left) to the final letter (right), and combining them to the whole word (Frith, 1985; Marsh et al., 1977; Roberts, 2003; van den Boer & de Jong, 2015). In skilled readers this strategy can be observed in a similar way for non-word reading (G. D. A. Brown & Deavers, 1999) and is more typical for consistent orthographies (e.g., German) than for inconsistent orthographies (e.g., English; Goswami, Ziegler, Dalton & Schneider, 2003)

If the letters in the strings are randomly shuffled, they do not contain a lexical meaning. Hence, an orthographic strategy or lexical route is not utilized; rather, the previously developed strategy for unfamiliar words or non-words is used. However, it is a new finding that these strategies also appear for strings, which contain non-letters or unknown letters.

To summarize, the results of the current study support the idea of letter-specific processing strategies and extend them to the context of whole word reading. Thereby, we closed a gap between letter-specific processing strategies, which could be observed while processing single letters, and reading strategies, which are shown for whole word reading tasks. The results fit into the dual-route models of reading and could be explained by an automatized integration of different stages of reading acquisition. Nevertheless, these strategies are not automatically triggered by the object, that should be processed, but rather are under cognitive control, depending on the knowledge which kind of material should be processed.

8. General discussion

The aim of this thesis was to improve our knowledge of letter-specific processing. Thereby, it was assumed, that letter processing is caused by specific processing strategies, developed during different stages of reading acquisition. Beside some constrains, influencing the appearance of letter-specific processing, in particular, the exclusion of some alternative hypotheses was in the focus this thesis.

The assumed letter-specific processing strategies are described as *analytic* and result from modifications of earlier developed object recognition strategies, which in contrast are described as *holistic* (see Lachmann & van Leeuwen, 2014, for a review). The prediction of analytic letter processing explains some findings of prior studies, for instance, mirror errors (Fernandes & Kolinsky, 2015; Lachmann, Schumacher & van Leeuwen, 2009; Lachmann & van Leeuwen, 2007) and congruency effects (Fernandes et al., 2014; Lachmann, Steinbrink et al., 2009; Lachmann & van Leeuwen, 2004, 2008b; van Leeuwen & Lachmann, 2004). To enable appropriate reading skills these letter processing strategies have to be automatized during a long phase of training (Blomert, 2011; Lachmann, Steinbrink et al., 2009). However, the alternative hypotheses constitute the distinction of letter and non-letter processing by the influence of *familiarity* or *nameability* instead of specific strategies. The current results ruled out these hypotheses as crucial explanations for letter-specific processing. However, the influence of familiarity or nameability rather seems to be moderated by the predicted strategies. Moreover, automatization was distinguished as the crucial factor of effective letter processing. Hence, the following sections will summarize and combine the current findings to support and improve the understanding of letter-specific processing strategies.

8.1. Temporal and visual constraints of letter processing

Theories of reading acquisition emphasize the role of automatization of letter processing to enable fluent reading (Ehri, 1995; Frith, 1986; Lachmann & van Leeuwen, 2014), however, during reading acquisition, evidently, letters become also more familiar objects. Automatization constitutes in particular two aspects: automatized processing is (1) very fast and (2) sensitive for the context in which the automatization occurred. In contrast, familiarity indeed increases processing speed, however, it depends less on the specific context. The results of Study 1, together with prior findings, clearly support the idea of automatized processes and reduce the explanatory power of familiarity.

Many studies showed a distinction in congruency effects for surrounded letters and non-letters (Fernandes et al., 2014; Lachmann, Steinbrink et al., 2009; Lachmann & van Leeuwen, 2004, 2008b; van Leeuwen & Lachmann, 2004). Depending on the specific instruction a negative congruency effect was observed for letters, whereas a positive congruency effect was observed for non-letters. As shown by Lachmann and van Leeuwen (2008a) the appearance of letter-specific effects also depends crucially on the time course of stimulus processing. The current results suggest, that this time course also is moderated by the experimental design. If holistic non-letter processing strategies are promoted by presenting non-letters twice as often as letters, the time course in which letter-specific processing occurs is much more restricted than in a balanced design. Assuming that the analytic as well as the holistic strategies are processed in parallel, promoting of the holistic processing strategies decreases the influence of the analytic processing strategies.

Hence, the appearance of letter-specific effects is restricted to a time frame in which the benefit of automatization is still given. The modulation of the holistic and analytic strategies is in accordance with prior studies, showing that the analytic strategies were preferred, if the categorial identity of letters was involved to solve a specific task, whereas the holistic strategies were preferred, if the processing was based on visual stimulus features (Lachmann & van Leeuwen, 2004; van Leeuwen & Lachmann, 2004). Although familiarity can explain why letters are processed very fast, it offers no explanation why the letter-specific effects vanish

for an imbalanced experimental design. Letters are still familiar objects, independently from how often they are presented. The results of Study 4 provide additional information about the time course of letter and non-letter processing, suggesting that the activation of specific strategies is not just caused by the stimuli itself, but rather by the expectation which kind of material should be processed. Specific strategies can be triggered also for mixed stimulus material, depending whether participants are asked to detect letters or non-letters. Hence, the preference for specific strategies can be determined in advance even before the stimulus appears. In contrast, familiarity can explain why letters are processed faster than non-letters in mixed character strings, but not why letters and non-letters are processed in different ways.

The familiarity hypothesis fails also to explain the result of the global-local task (Study 1, Experiment 2). Familiar objects falling into the visual field are detected very fast, independently, from the visual angle in which the object appears as long as the detectability is not impaired¹. Hence, familiarity can not explain, why letter-specific effects are restricted to crucial visual threshold. However, just this crucial threshold indicates an influence of automatization, which is, as mentioned before, very sensitive to context effects. Since reading usually occurs under specific visual conditions (e.g., the visual angle under which whole words and single letters normally appear), it is obvious that these conditions trigger automatized letter-specific processing strategies. On the one hand, automatized processes are benefited in a context, similar to the context in which the automatization occurred, and on the other hand, the influence of automatization decreases with increasing deviation from these conditions. This assumption underlies the feature integration approach (see van Leeuwen & Lachmann, 2004), suggesting that letter processing is driven by the categorial and contextual features and results from automatization during reading acquisition.

The explored temporal and visual constraints suggest two aspects of letter processing: First, automatized letter-specific processing strategies seems to fit better to the current findings than the familiarity hypothesis, and second, these

¹Of course, very large objects, falling out of the visual field, or very small objects with many details are not detected that easily. The assumption holds for more simple shapes, like the ones we used in the current studies.

processes occur in a very early stage of perceptual processes and are sensitive for the context in which the automatization usually occurs.

8.2. Transferability of letter-specific processing strategies

The neuronal recycling theory predicts that reading is based on neuronal structures, which were originally developed for object recognition (Dehaene & Cohen, 2007). Since reading requires specific skills, which are different to the common object recognition skills (e.g., symmetry suppression instead of symmetry generalization), these neuronal structures have to be modified during reading acquisition to enable efficient letter and word detection and processing. Thus, it is assumed that letter detection is just a special form of object recognition and that processing strategies which are involved in reading results from "recycling" of object recognition strategies. Since the neuronal recycling theory emphasizes the role of neuronal modification more than the role of automatization, it should be easy to transfer the modified object recognition strategies to new shapes, if they were ascribed to be letters.

However, the results in Study 2 demonstrated that new shapes are not completely assimilated as new letters even after training. Although these shapes were processed faster after training, reflecting a higher degree of familiarity, the typical effects for letter were not observed. On the one hand, the results indicate again that the distinction between letters and non-letters is not caused by familiarity. On the other hand, a simple shape-phoneme association is also not sufficient to initiate letter-specific processing. Thus, nameability alone does also not explain the observed distinction between letters and non-letters. Acquiring letter-specific processing strategies seems to be more than simple "recycling", instead, it is a result of a long-term training, performed separately for each single letter. It is not sufficient to modify specific neuronal structures to develop specific letter processing strategies during reading acquisition – these strategies have to be automatized. Hence, the *functional coordination model* (Lachmann & van Leeuwen, 2014) seems to fit better to the results than the neuronal recycling theory. In addition

to recruiting and modification of pre-existing skills, this model assumes a phase of coordination. This phase includes the integration of the auditory and visual domains to decode letters in a cross-modal mode and establish grapheme-phoneme associations. However, coordination alone is not sufficient to induce letter-specific processing strategies. Hence, the functional coordination model emphasizes the role of automatization. Letter processing has to be automatized for each letter separately. Thus, the analytic letter processing strategies cannot get transferred by a simple shape-phoneme association.

Automatization is also an essential part in other models of reading acquisition. Although it is not mentioned explicitly, automatization is very close to what some authors call the "development of reading speed". There was a debate whether this development of reading speed occurs simultaneously to the medial phases of reading acquisition (Chall, 1983) or subsequent to all other phases (Ehri, 1998), but there was consensus that each stage requires extensive training to prepare the following stage. This training is not restricted to establishing graphemes-phoneme rules, but rather involves processing of lexical and semantic content. Hence, independently from the model of reading acquisition, reading results from a process of procedural learning, requiring a long and extensive phase of training. This assumption is obvious, if we consider how long it takes to develop basic reading skills during elementary school and how long it lasts to improve these skills to enable fluent reading. Reading skills and thereby letter processing strategies cannot be easily transferred or "recycled". They have to be developed during a long phase of modification and coordination of prior developed skills, training, and automatization.

8.3. Letter processing and reading skills

Fluent reading requires a sufficient automatization of letter processing strategies. Hence, the degree of reading skills correlates with the degree of automatization. Prior studies demonstrated that children diagnosed with reading disabilities show less automatization or even a lack of automatized reading and letter processing strategies (e.g., Biscaldi et al., 1998; Blomert, 2011; Farah, Stowe & Levinson, 1996; Fernandes et al., 2014; Lachmann, Schumacher & van Leeuwen, 2009; Lach-

mann, Steinbrink et al., 2009; Lachmann & van Leeuwen, 2007, 2008b; Pollatsek, 1993). Specific reading difficulties are diagnosed in different domains, which are essential for efficient reading, for instance, in phonological awareness or rapid naming. However, common for all kinds of reading difficulties seems to be an impaired modification and coordination of different domains, disturbing a sufficient automatization. Thus, for example, Lachmann, Steinbrink et al. (2009) demonstrated different congruency effects in subgroups of developmental dyslexia. Whereas in normal skilled readers the analytic letter processing strategies attenuate the influence of irrelevant context, in dyslexics letters are processed much more context-sensitive. Fernandes et al. (2014) showed, that even illiterates profit from letter-specific processing strategies, depending on their degree of letter knowledge, however, for dyslexics, these strategies seemed to be completely missed. The absence of letter-specific strategies in dyslexics was also demonstrated for symmetry generalization, respectively, symmetry suppression. Since letters are characterized by their specific orientation, symmetry generalization has to be suppressed to enable proper letter recognition. For example, the graphemes and <d> are mirror images, but represent different phonemes. Lachmann and van Leeuwen (2007) showed, that this symmetry suppression for letters is not automatized in dyslexics.

Lachmann (2002) proposed that reading disabilities are caused by deficits of functional coordination. To enable sufficient letter processing earlier developed skills in the visual and auditory domain have to be modified and coordinated. For example, words have to be decomposed into phonemes. Afterwards, these phonemes and the associated graphemes are decoded in a cross-modal fashion (Blomert, 2011). During a long phase of training these cross-modal representations become automatized (Lachmann, Schumacher & van Leeuwen, 2009). This automatization is essential to enable fast letter detection and fluent reading. Hence, deficits in coordination or automatization lead to reading difficulties.

As shown in Study 3, this lack of automatization affects not perceptual but rather cognitive processes. The global precedence effect implies, firstly, that for the global level of hierarchical, compound figures is processed faster than the local level (*global advantage*). Second, the identity of the global level influences the processing of the local level, but not vice versa (*asymmetric interference*). The

global advantage was explained by perceptual and sensory mechanisms whereas the asymmetric interference was explained by cognitive processes, leading to a response conflict (see Kimchi, 1992, for a review). The interference indicates a response conflict, which is caused by an automatized processing of the global level, even if this level has to be ignored. Poirel, Pineau and Mellet (2008) demonstrated that this automatized processing is limited to letters or nameable objects, but not to meaningless symbols. As shown in Study 1 and 2, the automatized processing of letters leads also to interference from the local to the global level under specific conditions. The results of Study 3 suggest that even for 4th-grade children with normal reading skills, letter processing is already automatized to a certain degree. For these children the global advantage as well as the asymmetric interference was observed. Children with poor reading abilities showed no interference, neither from local to global nor from global to local, indicating a lack of automatized letter processing. However, the global advantage, which was explained by sensory mechanisms, was also observed for children with poor reading abilities. Thus, it can be assumed, that the underlying perceptual processes are similar for both groups, but that automatic letter processing only occurs in children with normal reading skills.

The current findings cannot explain, whether the lack of automatization causes reading difficulties or is a result of poor reading abilities. Nevertheless, the findings support the assumption of the functional coordination deficit hypothesis that automatized letter processing is essential component of appropriate reading skills.

8.4. Letter processing in whole word reading

Models of reading acquisition predict different phases, which are characterized by specific reading strategies (e.g., Ehri, 1995; Frith, 1985, 1986). Reading beginners start with the awareness, that written words represent spoken language. Moreover, they are able to recognize frequently written words, as for instance, environmental prints. Thereby, these words are perceived as a whole structure, without considering single letters as meaningful units. During medial phases letters become more important by establishing the GPC rules. During this phases words are

sequentially decoded in a letter-by-letter fashion. Increasing reading expertise is characterized by an enlargement of meaningful units, i.e., letters are connected to multi-letter units as morphemes or syllables. In advanced readers this *unitization* (Ehri, 1983) also includes familiar whole words. This whole word reading strategy enables readers to correctly pronounce even irregular spelled words. Although the latter strategy seems to be the more effective and the more advanced, it is assumed that while reading also the other strategies are still processed in parallel.

This parallel processing of different reading strategies is described in the dual-route models of reading (e.g., Coltheart, 1980; Coltheart et al., 1993; Ziegler et al., 2000), predicting a *lexical route* and a *non-lexical route*. The latter route describes the letter-by-letter reading strategy following the GPC rules. The lexical route concerns the whole word reading strategy, based on the identification of specific cue letters.

As discussed before, for proper letter detection, automatization of specific letter processing strategies is indispensable. Hence, it seems likely that also the strategies which are essential for word recognition have to be automatized to enable fluent reading. The findings of the global-local paradigm in Study 1 and 2 affirm this hypothesis. The both sided interference from the global to the local level as well as from the local to the global level indicates that both levels were processed in parallel. Although the stimuli were very different to real words, the specific reading-like conditions in which the stimuli were presented seem to trigger the parallel processing of the letter and the word level. Furthermore, the interference from the local to the global level indicates that processing of the global word level involves the processing of local sub-elements, as it would be expected for the cue-based whole word reading strategy. In contrast, to the logographic strategy (in reading beginners) in which words are perceived as a whole structure, the advanced orthographic strategy is based on detection of smaller word units or even single letters. Thus, recognition of the whole word requires processing of smaller sub-elements. The fact, that this parallel processing was observed in stimuli, which are obviously different to real words, suggests that these strategies occur automatically as soon as letters have to be processed.

With more word-like material similar results were observed in Study 4. In the five-character strings non-letter detection was based on a center-out screening,

caused by sensory mechanisms and resulting in a quadratic U-shaped function. This quadratic function is expected for a more holistic processing, indicating a symmetric target search strategy from the center to the terminal position. In contrast, the linear letter detection function indicates a more systematic target search. Hence, the letter detection function can be described as analytic. On the one hand, this finding underlies the strength of automatization in the context of letter and word processing. The presented stimuli in principle were the same for the letter and the non-letter condition, meaning that only the nature of the target influenced the chosen strategy and not the stimuli itself. On the other hand, the findings expand the hypothesis of specific analytic letter processing strategies to the context of whole word reading.

In transparent orthographies this analytic word reading results in a linear left-to-right trend, indicating a strong influence of the non-lexical letter-by-letter decoding strategy. It can be assumed, that for more intransparent orthographies, like English, the influence of the lexical route is more dominant, and therefore, the linear function merges to a more M-shaped function, which was observed in prior studies (e.g., Hammond & Green, 1982; Ktori & Pitchford, 2009; Mason, 1982; Mason & Katz, 1976). This needs to be a subject of further research to examine whether the predicted analytic whole word reading strategy differs between different orthographies. Nevertheless, the current results underly the role of automatization and specific letter processing strategies, as a result of different phases of reading acquisition.

9. Summary and Conclusion

The current thesis substantiates the role of automatized letter-specific processing strategies. Derived from different phases of reading acquisition, these strategies are a result of modification and coordination of earlier developed object recognition strategies. Their effectivity goes along with the degree of automatization. Conventional object recognition strategies are based on holistic processing, which are proven to be very efficient for common requests. Due to the specific requests of reading, letter and word processing strategies are more analytic, allowing proper letter distinction and parallel processing of letters and words. Specific constraints and features of these analytic letter processing strategies were part of the current studies. It was demonstrated that the context in which the automatization occurs, limits the efficiency of letter processing. Fast processing and reading-like conditions are crucial for the appearance of letter-specific strategies. With increasing influence of automatization, the influence of familiarity or nameability decreases. Further research should examine these specific conditions more systematically, to figure out whether there is a slight transition between holistic and analytic processing, or whether these strategies are mutually distinct and there is a crucial threshold in which one strategy completely replaces the other.

Another point suggesting the importance of automatization is illustrated by the fact that letter-specific processing strategies cannot be transferred that easily. They have to be established during a long phase of procedural training. However, it is not clear whether the strategies are really developed stepwise or whether there is a smooth transition from one phase to the other one. Although a lot of work was done in this area, this question has to be subject of further research.

Assuming the importance of automatization, it is not surprising that reading difficulties correlate with less automatized processing. Prior studies demonstrated that letter processing differs between normally skilled readers and dyslexics. These

findings were improved by the current results. The lack of automatization also influences a more global processing, indicating that in poor readers not only letter processing is impaired, but also the processing on word level. However, since the current findings were observed in a paradigm using more abstract stimuli, the same findings should be replicated in further studies using more word-like material to underline this hypothesis.

Yet, the last study indicated that also for more word-like material similar processes, as observed for the Navon figures, can be assumed. It was demonstrated that also the processing of the global word level depends on reading specific strategies and differs from usual object recognition strategies. This shows that the analytic strategy is not restricted to single letters but occurs also in whole word processing. These strategies are not activated spontaneously, depending whether or not words are presented, but rather are primed, depending on the knowledge, which kind of material should be processed. Since prior studies mostly focused on the impact of letter-specific processing strategies rather than the origin or activators of these strategies, the priming of letter-specific processing can give new evidences for the underlying cognitive processes, and hence, should be considered as an initial point for further research in this field.

This thesis has shown that effective letter processing requests more than simple sensory mechanisms, moderated by familiarity or nameability. Letter processing is based on cognitive processes, inducing analytic letter processing strategies as a result of modification and coordination of earlier developed object recognition strategies during reading acquisition. Learning to read requires a long phase of procedural learning, resulting in automatized activation and usage of letter-specific processing strategies.

References

- Ahissar, M., Protopapas, A., Reid, M. & Merzenich, M. M. (2000). Auditory processing parallels reading abilities in adults. *Proceedings of the National Academy of Sciences*, *97*(12), 6832–6837. doi: 10.1073/pnas.97.12.6832
- Ahmed, L. & Fockert, J. W. (2012). Working memory load can both improve and impair selective attention: Evidence from the Navon paradigm. *Attention, Perception, & Psychophysics*, *74*(7), 1397–1405. doi: 10.3758/s13414-012-0357-1
- Alloway, T. P., Gathercole, S. E., Willis, C. & Adams, A. M. (2004). A structural analysis of working memory and related cognitive skills in young children. *Journal of Experimental Child Psychology*, *87*(2), 85–106. doi: 10.1016/j.jecp.2003.10.002
- Amirkhiabani, G. (1998). Relative size of global visual stimulus: Advantage and interference. *Perceptual and Motor Skills*, *86*, 1427–1441. doi: 10.2466/pms.1998.86.3c.1427
- Amirkhiabani, G. & Lovegrove, W. J. (1996). Role of eccentricity and size in the global precedence effect. *Journal of Experimental Psychology: Human Perception and Performance*, *22*(6), 1434–1447. doi: 10.1037/0096-1523.22.6.1434
- Andrews, S. (1997). The effect of orthographic similarity on lexical retrieval: Resolving neighborhood conflicts. *Psychonomic Bulletin & Review*, *4*(4), 439–461. doi: 10.3758/BF03214334
- Au, A. & Lovegrove, B. (2007). The contribution of rapid visual and auditory processing to the reading of irregular words and pseudowords presented singly and in contiguity. *Perception & Psychophysics*, *69*(8), 1344–59. doi: 10.3758/BF03192951
- Augst, G. (1986). Descriptively and explanatorily adequate models of orthography.

- In G. Augst (Ed.), *New trends in graphemics and orthography* (pp. 25–42). Berlin; New York: de Gruyter.
- Ayres, J. J. (1966). Some artifactual causes of perceptual primacy. *Journal of Experimental Psychology*, *71*(6), 896–901. doi: 10.1037/h0023196
- Badcock, D. & Lovegrove, W. (1981). The effects of contrast, stimulus duration, and spatial frequency on visible persistence in normal and specifically disabled readers. *Journal of Experimental Psychology: Human Perception and Performance*, *7*(3), 495–505. doi: 10.1037//0096-1523.7.3.495
- Baddeley, A. (1979). Working memory and reading. In P. A. Kolers, M. E. Wrolstad & H. Bouma (Eds.), *Processing of visible language* (pp. 355–370). Boston, MA: Springer US. doi: 10.1007/978-1-4684-0994-9
- Baddeley, A. (1982). Reading and working memory. *Bulletin of the British Psychological Society*, *35*, 414–417.
- Baddeley, A. (2003). Working memory and language: An overview. *Journal of Communication Disorders*, *36*(3), 189–208. doi: 10.1016/S0021-9924(03)00019-4
- Balmuth, M. (1982). *The roots of phonics, a historical introduction*. New York: McGraw-Hill.
- Baron, J. (1977). Mechanisms for pronouncing printed words: Use and acquisition. In D. LaBerge & S. J. Samuels (Eds.), *Basic processes in reading: Perception and comprehension* (pp. 175–216). Hillsdale NJ: Erlbaum.
- Baron, J. (1979). Orthographic and word-specific mechanisms in children's reading of words. *Child Development*, *50*(1), 60–72. doi: 10.2307/1129042
- Baron, J. & McKillop, B. J. (1975). Individual differences in speed of phonemic analysis, visual analysis, and reading. *Acta Psychologica*, *39*(2), 91–96. doi: 10.1016/0001-6918(75)90001-3
- Baron, J. & Strawson, C. (1976). Use of orthographic and word-specific knowledge in reading words aloud. *Journal of Experimental Psychology: Human Perception and Performance*, *2*(3), 386–393. doi: 10.1037/0096-1523.2.3.386
- Bavelier, D., Deruelle, C. & Proksch, J. (2000). Positive and negative compatibility effects. *Perception & Psychophysics*, *62*(1), 100–112. doi: 10.3758/BF03212064
- Beaucousin, V., Cassotti, M., Simon, G., Pineau, A., Kostova, M., Houdé, O. &

- Poirel, N. (2011). ERP evidence of a meaningfulness impact on visual global/local processing: When meaning captures attention. *Neuropsychologia*, *49*(5), 1258–1266. doi: 10.1016/j.neuropsychologia.2011.01.039
- Becker, C., Elliott, M. A. & Lachmann, T. (2005). Evidence for impaired visuoperceptual organisation in developmental dyslexics and its relation to temporal processes. *Cognitive Neuropsychology*, *22*(5), 499–522. doi: 10.1080/02643290442000086
- Biscaldi, M., Gezeck, S. & Stuhr, V. (1998). Poor saccadic control correlates with dyslexia. *Neuropsychologia*, *36*(11), 1189–1202. doi: 10.1016/S0028-3932(97)00170-X
- Blank, S. C., Scott, S. K., Murphy, K., Warburton, E. & Wise, R. J. (2002). Speech production: Wernicke, Broca and beyond. *Brain*, *125*(8), 1829–1838. doi: 10.1093/brain/awf191
- Blau, V., Reithler, J., Van Atteveldt, N., Seitz, J., Gerretsen, P., Goebel, R. & Blomert, L. (2010). Deviant processing of letters and speech sounds as proximate cause of reading failure: A functional magnetic resonance imaging study of dyslexic children. *Brain*, *133*(3), 868–879. doi: 10.1093/brain/awp308
- Blomert, L. (2011). The neural signature of orthographic-phonological binding in successful and failing reading development. *NeuroImage*, *57*(3), 695–703. doi: 10.1016/j.neuroimage.2010.11.003
- Boets, B., Wouters, J., van Wieringen, A., De Smedt, B. & Ghesquière, P. (2008). Modelling relations between sensory processing, speech perception, orthographic and phonological ability, and literacy achievement. *Brain and Language*, *106*(1), 29–40. doi: 10.1016/j.bandl.2007.12.004
- Boucart, M. & Humphreys, G. (1992). Global shape cannot be attended without object identification. *Journal of Experimental Psychology: Human Perception and Performance*, *18*(3), 785–806. doi: 10.1037/0096-1523.18.3.785
- Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, *226*(5241), 177–178. doi: 10.1038/226177a0
- Bouvet, L., Rousset, S., Valdois, S. & Donnadieu, S. (2011). Global precedence effect in audition and vision: Evidence for similar cognitive styles across modalities. *Acta Psychologica*, *138*(2), 329–335. doi: 10.1016/j.actpsy.2011.08.004

- Bowers, P. G., Golden, J., Kennedy, A. & Young, A. (1994). Limits upon orthographic knowledge due to processes indexed by naming speed. In V. W. Berninger (Ed.), *The varieties of orthographic knowledge* (1st ed., pp. 173–218). Dordrecht, Netherlands: Springer Netherlands. doi: 10.1007/978-94-017-3492-9_6
- Bowers, P. G. & Wolf, M. (1993). Theoretical links among naming speed, precise timing mechanisms and orthographic skill in dyslexia. *Reading and Writing*, 5(1), 69–85. doi: 10.1007/BF01026919
- Breitmeyer, B. G. (1989). A visually based deficit in specific reading disability. *The Irish Journal of Psychology*, 10(4), 534–541. doi: 10.1080/03033910.1989.10557768
- Briand, K. A. (1994). Selective attention to global and local structure of objects: Alternative measures of nontarget processing. *Perception & Psychophysics*, 55(5), 562–574. doi: 10.3758/BF03205313
- Brown, G. D. A. & Deavers, R. P. (1999). Units of analysis in nonword reading: Evidence from children and adults. *Journal of Experimental Child Psychology*, 73(3), 208–242. doi: 10.1006/jecp.1999.2502
- Brown, T. T., Lugar, H. M., Coalson, R. S., Miezin, F. M., Petersen, S. E. & Schlaggar, B. L. (2005). Developmental changes in human cerebral functional organization for word generation. *Cerebral Cortex*, 15(3), 275–90. doi: 10.1093/cercor/bhh129
- Bryden, M. P. (1967). A model for the sequential organization of behaviour. *Canadian Journal of Psychology*, 21(1), 37–56. doi: 10.1037/h0082960
- Burgund, E. D. & Abernathy, A. E. (2008). Letter-specific processing in children and adults matched for reading level. *Acta Psychologica*, 129(1), 66–71. doi: 10.1016/j.actpsy.2008.04.007
- Castles, A. & Coltheart, M. (1993). Varieties of developmental dyslexia. *Cognition*, 47(2), 149–180. doi: 10.1016/0010-0277(93)90003-E
- Chall, J. S. (1983). *Learning to read: The great debate*. New York, NY: McGraw-Hill.
- Chanceaux, M. & Grainger, J. (2012). Serial position effects in the identification of letters, digits, symbols, and shapes in peripheral vision. *Acta Psychologica*, 141(2), 149–158. doi: 10.1016/j.actpsy.2012.08.001

- Chase, P. G. & Dibble, H. L. (1987). Middle paleolithic symbolism: A review of current evidence and interpretations. *Journal of Anthropological Archaeology*, 6(3), 263–296. doi: 10.1016/0278-4165(87)90003-1
- Clark, C. R., Brruininks, R. H. & Galman, G. V. (1978). Kindergarten predictors of three aspects of reading achievement. *Perceptual and Motor Skills*, 46(2), 411–419. doi: 10.2466/pms.1978.46.2.411
- Cohen, L. (2002). Language-specific tuning of visual cortex? Functional properties of the visual word form area. *Brain*, 125(5), 1054–1069. doi: 10.1093/brain/awf094
- Cohen, L., Dehaene, S., Naccache, L., Lehéricy, S., Dehaene-Lambertz, G., Hénaff, M. A. & Michel, F. (2000). The visual word form area: Spatial and temporal characterization of an initial stage of reading in normal subjects and posterior split-brain patients. *Brain*, 123, 291–307. doi: 10.1093/brain/123.2.291
- Coltheart, M. (1980). Reading phonological recoding, and deep dyslexia. In M. Coltheart, K. Patterson & J. C. Marshall (Eds.), *Deep dyslexia* (pp. 197–226). London, UK: Routledge & Kegan Paul.
- Coltheart, M. (1986). Graphemics and visual word recognition. In G. Augst (Ed.), *New trends in graphemics and orthography*. Berlin, Germany: de Gruyter.
- Coltheart, M. (2006). Acquired dyslexias and the computational modelling of reading. *Cognitive Neuropsychology*, 23(1), 96–109. doi: 10.1080/02643290500202649
- Coltheart, M. (2007). Modeling reading: The dual-route approach. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 6–23). Oxford, UK: Blackwell Publishing. doi: 10.1002/9780470757642.ch1
- Coltheart, M., Curtis, B., Atkins, P. & Haller, M. (1993). Models of reading aloud: Dual-route and parallel-distributed-processing approaches. *Psychological Review*, 100(4), 589–608. doi: 10.1037/0033-295X.100.4.589
- Coltheart, M., Davelaar, E. J., Jonasson, J. T. & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance* (pp. 64–85). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Coltheart, M., Rastle, K., Perry, C., Langdon, R. & Ziegler, J. (2001). DRC: a dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, 108(1), 204–56. doi: 10.1037/0033-295X.108.1.204

- Conrad, R. (1964). Acoustic confusions in immediate memory. *British Journal of Psychology*, *55*(1), 75–84. doi: 10.1111/j.2044-8295.1964.tb00899.x
- Corballis, M. C. (1988). Recognition of disoriented shapes. *Psychological Review*, *95*(1), 115–23. doi: 10.1037/0033-295X.95.1.115
- Crowder, R. G. & Wagner, R. K. (1992). *The psychology of reading: An introduction* (2nd ed.). New York, NY: Cambridge University Press.
- Davidoff, J., Fonteneau, E. & Fagot, J. (2008). Local and global processing: Observations from a remote culture. *Cognition*, *108*(3), 702–709. doi: 10.1016/j.cognition.2008.06.004
- Davidson, I. & Noble, W. (1989). The archaeology of depiction and language. *Current Anthropology*, *30*(2), 125–156. doi: 10.1086/203723
- De Saussure, F. (1922). *Recueil des publications scientifiques de Ferdinand de Saussure*. Genève, Swiss: Société anonyme des éditions Sonor.
- Deavers, R., Solity, J. & Kerfoot, S. (2000). The effect of instruction on early nonword reading strategies. *Journal of Research in Reading*, *23*(3), 267–286. doi: 10.1111/1467-9817.00122
- Dehaene, S. & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron*, *56*(2), 384–398. doi: 10.1016/j.neuron.2007.10.004
- Dickinson, D. K. & Tabors, P. O. (1991). Early literacy: Linkages between home, school and literacy achievement at age five. *Journal of Research in Childhood Education*, *6*(1), 30–46. doi: 10.1080/02568549109594820
- Dickinson, D. K. & Tabors, P. O. (Eds.). (2001). *Building literacy with language: Young children learning at home and school*. Baltimore, MD: Brookes.
- Doctor, E. A. & Coltheart, M. (1980). Children's use of phonological encoding when reading for meaning. *Memory & Cognition*, *8*(3), 195–209. doi: 10.3758/BF03197607
- Dulaney, C. L. & Marks, W. (2007). The effects of training and transfer on global/local processing. *Acta Psychologica*, *125*(2), 203–220. doi: 10.1016/j.actpsy.2006.07.001
- Eden, G. F., Stein, J. F., Wood, H. M. & Wood, F. B. (1994). Differences in eye movements and reading problems in dyslexic and normal children. *Vision Research*, *34*(10), 1345–58. doi: 10.1016/0042-6989(94)90209-7
- Ehri, L. C. (1979). Linguistic insight: Threshold of reading acquisition. In

- T. Waller & G. McKinnon (Eds.), *Reading research: Advances in theory and practice* (pp. 63–114). New York, NY: Academic Press.
- Ehri, L. C. (1983). A critique of five studies related to letter-name knowledge and learning to read. In L. M. Gentile, M. L. Kamil & J. Blanchard (Eds.), *Reading research revisited* (1st ed., pp. 143–153). New York, NY: Academic Press.
- Ehri, L. C. (1995). Phases of development in learning to read words by sight. *Journal of Research in Reading*, 18(2), 116–125. doi: 10.1111/j.1467-9817.1995.tb00077.x
- Ehri, L. C. (1998). Grapheme-phoneme knowledge is essential for learning to read words in English. In J. L. Metsala & L. C. Ehri (Eds.), *Word recognition in beginning literacy* (pp. 3–40). Mahwah, NJ: Lawrence Erlbaum Associates.
- Ehri, L. C. (1999). Phases of development in learning to read words. In J. Oakhill & R. Beard (Eds.), *Reading development and the teaching of reading: A psychological perspective* (pp. 79–108). Oxford, UK: Blackwell Publishing.
- Ehri, L. C. (2007). Development of sight word reading: Phases and findings. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 135–154). Oxford, England: Blackwell Publishing. doi: 10.1002/9780470757642.ch8
- Ehri, L. C. & Wilce, L. S. (1985). Movement into reading: Is the first stage of printed word learning visual or phonetic? *Reading Research Quarterly*, 20(2), 163. doi: 10.2307/747753
- Eriksen, B. A. & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, 16(1), 143–149. doi: 10.3758/BF03203267
- Estes, W. K. (1972). Interactions of signal and background variables in visual processing. *Perception & Psychophysics*, 12(3), 278–286. doi: 10.3758/BF03207204
- Estes, W. K. (1982). Similarity-related channel interactions in visual processing. *Journal of Experimental Psychology: Human Perception and Performance*, 8(3), 353–382. doi: 10.1037/0096-1523.8.3.353
- Farah, M. J., Stowe, R. M. & Levinson, K. L. (1996). Phonological dyslexia: Loss of a reading-specific component of the cognitive architecture? *Cognitive*

- Psychology*, 13(6), 849–868. doi: 10.1080/026432996381836
- Farid, M. & Grainger, J. (1996). How initial fixation position influences visual word recognition: A comparison of French and Arabic. *Brain and Language*, 53(3), 351–368. doi: 10.1006/brln.1996.0053
- Farmer, M. E. & Klein, R. M. (1995). The evidence for a temporal processing deficit linked to dyslexia: A review. *Psychonomic Bulletin & Review*, 2(4), 460–93. doi: 10.3758/BF03210983
- Fernandes, T. & Kolinsky, R. (2013). From hand to eye: The role of literacy, familiarity, graspability, and vision-for-action on enantiomorphy. *Acta Psychologica*, 142(1), 51–61. doi: 10.1016/j.actpsy.2012.11.008
- Fernandes, T. & Kolinsky, R. (2015). The impact of learning to read on visual processing. *Frontiers in Psychology*, 6, 985. doi: 10.3389/fpsyg.2015.00985
- Fernandes, T., Vale, A. P., Martins, B., Morais, J. & Kolinsky, R. (2014). The deficit of letter processing in developmental dyslexia: Combining evidence from dyslexics, typical readers and illiterate adults. *Developmental Science*, 17(1), 125–141. doi: 10.1111/desc.12102
- Fischer, B. & Hartnegg, K. (2008). Saccade control in dyslexia: Development, deficits, training and transfer to reading. *Journal of Optometric Vision Development*, 39(4), 181–190.
- Fletcher, J. M., Foorman, B., Shaywitz, S. E. & Shaywitz, B. A. (1999). Conceptual and methodological issues in dyslexia research: A lesson for developmental disorders. In H. Tager-Flusberg (Ed.), *Neurodevelopmental disorders* (pp. 271–306). Cambridge, MA; London, England: MIT Press.
- Förster, J. & Higgins, E. T. (2005). How global versus local perception fits regulatory focus. *Psychological Science*, 16(8), 631–636. doi: 10.1111/j.1467-9280.2005.01586.x
- Forster, K. I. & Chambers, S. M. (1973). Lexical access and naming time. *Journal of Verbal Learning and Verbal Behavior*, 12(6), 627–635. doi: 10.1016/S0022-5371(73)80042-8
- Foulin, J. N. (2005). Why is letter-name knowledge such a good predictor of learning to read? *Reading and Writing*, 18(2), 129–155. doi: 10.1007/s11145-004-5892-2
- Friederici, A. D. & Lachmann, T. (2002). From language to reading and read-

- ing disability: Cognitive functions and their neural basis. In E. Witruk, A. D. Friederici & T. Lachmann (Eds.), *Basic functions of language, reading and reading disability* (pp. 9–21). Boston, MA: Springer US. doi: 10.1007/978-1-4615-1011-6_2
- Friedman, R. B. (1996). Recovery from deep alexia to phonological alexia: points on a continuum. *Brain and Language*, 52(1), 114–28. doi: 10.1006/brln.1996.0006
- Frith, U. (1985). Beneath the surface of developmental dyslexia. In K. Patterson, J. C. Marshall & M. Coltheart (Eds.), *Surface dyslexia: Neuropsychological and cognitive studies of phonological reading* (pp. 301–330). London, UK: Lawrence Erlbaum Associates.
- Frith, U. (1986). A developmental framework for developmental dyslexia. *Annals of Dyslexia*, 36(1), 67–81. doi: 10.1007/BF02648022
- Froyen, D. J. W., Bonte, M. L., van Atteveldt, N. & Blomert, L. (2009). The long road to automation: Neurocognitive development of letter-speech sound processing. *Journal of Cognitive Neuroscience*, 21(3), 567–580. doi: 10.1162/jocn.2009.21061
- Froyen, D. J. W., Van Atteveldt, N., Bonte, M. & Blomert, L. (2008). Cross-modal enhancement of the MMN to speech-sounds indicates early and automatic integration of letters and speech-sounds. *Neuroscience Letters*, 430(1), 23–28. doi: 10.1016/j.neulet.2007.10.014
- Froyen, D. J. W., Willems, G. & Blomert, L. (2011). Evidence for a specific cross-modal association deficit in dyslexia: An electrophysiological study of letter-speech sound processing. *Developmental Science*, 14(4), 635–648. doi: 10.1111/j.1467-7687.2010.01007.x
- Füssenich, I. & Löffler, C. (2008). *Schriftspracherwerb Einschulung, erstes und zweites Schuljahr*. München: Ernst Reinhardt.
- Gable, P. A., Poole, B. D. & Cook, M. S. (2013). Asymmetrical hemisphere activation enhances global-local processing. *Brain and Cognition*, 83(3), 337–341. doi: 10.1016/j.bandc.2013.09.012
- Glosser, G. & Friedman, R. B. (1990). The continuum of deep/phonological alexia. *Cortex*, 26(3), 343–359. doi: 10.1016/S0010-9452(13)80085-8
- Goswami, U. (1990). A special link between rhyming skill and the use of or-

- thographic analogies by beginning readers. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, 31(2), 301–11. doi: 10.1111/j.1469-7610.1990.tb01568.x
- Goswami, U. (1993). Toward an interactive analogy model of reading development: Decoding vowel graphemes in beginning reading. *Journal of Experimental Child Psychology*, 56(3), 443–475. doi: 10.1006/jecp.1993.1044
- Goswami, U. (1999). Causal connections in beginning reading: The importance of rhyme. *Journal of Research in Reading*, 22(3), 217–240. doi: 10.1111/1467-9817.00087
- Goswami, U. (2011). A temporal sampling framework for developmental dyslexia. *Trends in Cognitive Sciences*, 15(1), 3–10. doi: 10.1016/j.tics.2010.10.001
- Goswami, U., Ziegler, J. C., Dalton, L. & Schneider, W. (2003). Nonword reading across orthographies: How flexible is the choice of reading units? *Applied Psycholinguistics*, 24(02), 235–247. doi: 10.1017/S0142716403000134
- Gough, P. B. (1996). How children learn to read and why they fail. *Annals of Dyslexia*, 46(1), 1–20. doi: 10.1007/BF02648168
- Grainger, J., Tydgate, I. & Issele, J. (2010). Crowding affects letters and symbols differently. *Journal of Experimental Psychology: Human Perception and Performance*, 36(3), 673–88. doi: 10.1037/a0016888
- Grainger, J. & Ziegler, J. C. (2011). A dual-route approach to orthographic processing. *Frontiers in Psychology*, 2, 54. doi: 10.3389/fpsyg.2011.00054
- Green, D. W., Hammond, E. J. & Supramaniam, S. (1983). Letters and shapes: Developmental changes in search strategies. *British Journal of Psychology*, 74(1), 11–16. doi: 10.1111/j.2044-8295.1983.tb01839.x
- Grice, G. R., Canham, L. & Boroughs, J. M. (1983). Forest before trees? It depends where you look. *Perception & Psychophysics*, 33(2), 121–128. doi: 10.3758/BF03202829
- Groth, K., Lachmann, T., Riecker, A., Muthmann, I. & Steinbrink, C. (2011). Developmental dyslexics show deficits in the processing of temporal auditory information in German vowel length discrimination. *Reading and Writing*, 24(3), 285–303. doi: 10.1007/s11145-009-9213-7
- Günther, K. B. (1986). Ein Stufenmodell der Entwicklung kindlicher Lese- und Schreibstrategien. In H. Brügelmann (Ed.), *ABC und Schriftspracherwerb*:

- Rätsel für Kinder, Lehrer und Forscher* (pp. 32–54). Konstanz: Faude.
- Guttentag, R. E. & Haith, M. M. (1978). Automatic processing as a function of age and reading ability. *Child Development*, *49*(3), 707–716. doi: 10.2307/1128239
- Haber, R. N. & Standing, L. (1969). Location of errors with a post-stimulus indicator. *Psychonomic Science*, *17*(6), 345–346. doi: 10.3758/BF03335273
- Hagenaar, R. & van der Heijden, A. H. (1986). Target-noise separation in visual selective attention. *Acta Psychologica*, *62*(2), 161–76. doi: 10.1016/0001-6918(86)90066-1
- Hämäläinen, J. A., Salminen, H. K. & Leppänen, P. H. T. (2013). Basic auditory processing deficits in dyslexia: Systematic review of the behavioral and event-related potential/field evidence. *Journal of Learning Disabilities*, *46*(5), 413–427. doi: 10.1177/0022219411436213
- Hammond, E. J. & Green, D. W. (1982). Detecting targets in letter and non-letter arrays. *Canadian Journal of Psychology*, *36*(1), 67–82. doi: 10.1037/h0081211
- Harcum, E. R. (1967). Parallel functions of serial learning and tachistoscopic pattern perception. *Psychological Review*, *74*(1), 51–62. doi: 10.1037/h0024099
- Harrison, T. B. & Stiles, J. (2009). Hierarchical forms processing in adults and children. *Journal of Experimental Child Psychology*, *103*(2), 222–240. doi: 10.1016/j.jecp.2008.09.004
- Heath, S. & Hogben, J. H. (2004). Cost-effective prediction of reading difficulties. *Journal of Speech, Language & Hearing Research*, *47*(4), 751–765. doi: 10.1044/1092-4388(2004/057)
- Heim, S., Grande, M., Pape-Neumann, J., van Ermingen, M., Meffert, E., Grabowska, A., ... Amunts, K. (2010). Interaction of phonological awareness and 'magnocellular' processing during normal and dyslexic reading: Behavioural and fMRI investigations. *Dyslexia*, *16*(3), 258–282. doi: 10.1002/dys.409
- Hermens, F., Lachmann, T. & van Leeuwen, C. (2013). Is it really search or just matching? The influence of Goodness, number of stimuli and presentation sequence in same-different tasks. *Psychological Research*, *79*(1), 42–63. doi: 10.1007/s00426-013-0529-1
- Heron, W. (1957). Perception as a function of retinal locus and attention. *The*

- American Journal of Psychology*, 70(1), 38–48.
- Higgins, E. T., Shah, J. & Friedman, R. (1997). Emotional responses to goal attainment: Strength of regulatory focus as moderator. *Journal of Personality and Social Psychology*, 72(3), 515–525. doi: 10.1037/0022-3514.72.3.515
- Hinshelwood, J. (1917). Congenital word-blindness. *The Lancet*, 190(4922), 980. doi: 10.1016/S0140-6736(01)56353-9
- Hood, M. & Conlon, E. (2004). Visual and auditory temporal processing and early reading development. *Dyslexia*, 10(3), 234–252. doi: 10.1002/dys.273
- Hübner, R. (1997). The effect of spatial frequency on global precedence and hemispheric differences. *Perception & Psychophysics*, 59(2), 187–201. doi: 10.3758/BF03211888
- Hughes, H. C., Layton, W. M., Baird, J. C. & Lester, L. S. (1984). Global precedence in visual pattern recognition. *Perception & Psychophysics*, 35(4), 361–371. doi: 10.3758/BF03206340
- Jolicoeur, P., Corballis, M. C. & Lawson, R. (1998). The influence of perceived rotary motion on the recognition of rotated objects. *Psychonomic Bulletin & Review*, 5(1), 140–146. doi: 10.3758/BF03209470
- Jordan, T. & Martin, C. (1987). The importance of visual angle in word recognition: A "shrinking screen" modification for visual displays. *Behavior Research Methods, Instruments, & Computers*, 19(3), 307–310. doi: 10.3758/BF03202566
- Jorm, a. F., Share, D. L., Maclean, R. & Matthews, R. (1984). Phonological confusability in short-term memory for sentences as a predictor of reading ability. *British Journal of Psychology*, 75(3), 393–400. doi: 10.1111/j.2044-8295.1984.tb01909.x
- Kavale, K. A. (1982). Meta-analysis of the relationship between visual perceptual skills and reading achievement. *Journal of Learning Disabilities*, 15(1), 42–51. doi: 10.1177/002221948201500110
- Kavale, K. A. & Forness, S. R. (2000). Auditory and visual perception processes and reading ability: A quantitative reanalysis and historical reinterpretation. *Learning Disability Quarterly*, 23(4), 253–270. doi: 10.2307/1511348
- Kimchi, R. (1988). Selective attention to global and local levels in the comparison of hierarchical patterns. *Perception & Psychophysics*, 43(2), 189–198. doi:

10.3758/BF03214197

- Kimchi, R. (1992). Primacy of wholistic processing and global/local paradigm: A critical review. *Psychological Bulletin*, *112*(1), 24–38. doi: 10.1037/0033-2909.112.1.24
- Kimchi, R., Amishav, R. & Sulitzeanu-Kenan, A. (2009). Gender differences in global-local perception? Evidence from orientation and shape judgments. *Acta Psychologica*, *130*(1), 64–71. doi: 10.1016/j.actpsy.2008.10.002
- Kimchi, R. & Merhav, I. (1991). Hemispheric processing of global form, local form, and texture. *Acta Psychologica*, *76*(2), 133–147. doi: 10.1016/0001-6918(91)90042-X
- Kimchi, R. & Palmer, S. E. (1982). Form and texture in hierarchically constructed patterns. *Journal of Experimental Psychology: Human Perception and Performance*, *8*(4), 521–35. doi: 10.1037/0096-1523.8.4.521
- Kinchla, R. A. (1974). Detecting target elements in multielement arrays: A confusability model. *Perception & Psychophysics*, *15*(1), 149–158. doi: 10.3758/BF03205843
- Kinchla, R. A. & Wolfe, J. M. (1979). The order of visual processing: "Top-down", "bottom-up", or "middle-out". *Perception & Psychophysics*, *25*(3), 225–231. doi: 10.3758/BF03202991
- Kirby, J. R., Georgiou, G. K., Martinussen, R., Parrila, R., Bowers, P. & Landerl, K. (2010). Naming speed and reading: From prediction to instruction. *Reading Research Quarterly*, *45*(3), 241–362. doi: 10.1598/RRQ.45.3.4
- Klatzky, R. L. & Stoy, A. M. (1974). Using visual codes for comparisons of pictures. *Memory & Cognition*, *2*(4), 727–36. doi: 10.3758/BF03198148
- Kleiman, G. M. (1975). Speech recoding in reading. *Journal of Verbal Learning and Verbal Behavior*, *14*(4), 323–339. doi: 10.1016/S0022-5371(75)80013-2
- Klein, R. G. (1995). Anatomy, behavior, and modern human origins. *Journal of World Prehistory*, *9*(2), 167–198. doi: 10.1007/BF02221838
- Ktori, M. & Pitchford, N. J. (2008). Effect of orthographic transparency on letter position encoding: A comparison of Greek and English monoscriptal and biscriptal readers. *Language and Cognitive Processes*, *23*(2), 258–281. doi: 10.1080/01690960701536797
- Ktori, M. & Pitchford, N. J. (2009). Development of letter position processing: Ef-

- fects of age and orthographic transparency. *Journal of Research in Reading*, 32(2), 180–198. doi: 10.1111/j.1467-9817.2009.01394.x
- Kuehn, S. M. & Jolicoeur, P. (1994). Impact of quality of the image, orientation, and similarity of the stimuli on visual search for faces. *Perception*, 23(1), 95–122. doi: 10.1068/p230095
- LaBerge, D. & Samuels, S. (1974). Toward a theory of automatic information processing in reading. *Cognitive Psychology*, 6(2), 293–323. doi: 10.1016/0010-0285(74)90015-2
- Lachmann, T. (2002). Reading disability as a deficit in functional coordination. In E. Witruk, A. D. Friederici & T. Lachmann (Eds.), *Basic functions of language, reading and reading disability* (pp. 165–198). Boston, MA: Springer US. doi: 10.1007/978-1-4615-1011-6_11
- Lachmann, T. (2007). *Basic determinants of specific learning disabilities in reading*. Kaiserslautern, Germany: Technische Universität Kaiserslautern.
- Lachmann, T. & Geissler, H.-G. (2002). Memory search instead of template matching? *Acta Psychologica*, 111(3), 283–307. doi: 10.1016/S0001-6918(02)00055-0
- Lachmann, T., Khera, G., Srinivasan, N. & van Leeuwen, C. (2012). Learning to read aligns visual analytical skills with grapheme-phoneme mapping: Evidence from illiterates. *Frontiers in Evolutionary Neuroscience*, 4, 8. doi: 10.3389/fnevo.2012.00008
- Lachmann, T., Schmitt, A., Braet, W. & van Leeuwen, C. (2014). Letters in the forest: Global precedence effect disappears for letters but not for non-letters under reading-like conditions. *Frontiers in Psychology*, 5, 705. doi: 10.3389/fpsyg.2014.00705
- Lachmann, T., Schumacher, B. & van Leeuwen, C. (2009). Controlled but independent: Effects of mental rotation and developmental dyslexia in dual-task settings. *Perception*, 38(7), 1019–1034. doi: 10.1068/p6313
- Lachmann, T., Steinbrink, C., Schumacher, B. & van Leeuwen, C. (2009). Different letter-processing strategies in diagnostic subgroups of developmental dyslexia also occur in a transparent orthography: Reply to a commentary by Spinelli et al. *Cognitive Neuropsychology*, 26(8), 759–68. doi: 10.1080/02643291003737065

- Lachmann, T. & van Leeuwen, C. (2004). Negative congruence effects in letter and pseudo-letter recognition: The role of similarity and response conflict. *Cognitive Processing*, 5(4), 239–248. doi: 10.1007/s10339-004-0032-0
- Lachmann, T. & van Leeuwen, C. (2007). Paradoxical enhancement of letter recognition in developmental dyslexia. *Developmental Neuropsychology*, 31(1), 61–77. doi: 10.1080/87565640709336887
- Lachmann, T. & van Leeuwen, C. (2008a). Differentiation of holistic processing in the time course of letter recognition. *Acta Psychologica*, 129(1), 121–129. doi: 10.1016/j.actpsy.2008.05.003
- Lachmann, T. & van Leeuwen, C. (2008b). Different letter-processing strategies in diagnostic subgroups of developmental dyslexia. *Cognitive Neuropsychology*, 25(5), 730–744. doi: 10.1080/02643290802309514
- Lachmann, T. & van Leeuwen, C. (2014). Reading as functional coordination: Not recycling but a novel synthesis. *Frontiers in Psychology*, 5(1046), 1–8. doi: 10.3389/fpsyg.2014.01046
- LaGasse, L. L. (1993). Effects of good form and spatial frequency on global precedence. *Perception & Psychophysics*, 53(1), 89–105. doi: 10.3758/BF03211718
- Lamb, M. R. & Robertson, L. C. (1988). The processing of hierarchical stimuli: Effects of retinal locus, locational uncertainty, and stimulus identity. *Perception & Psychophysics*, 44(2), 172–181. doi: 10.3758/BF03208710
- Lamb, M. R. & Robertson, L. C. (1990). The effect of visual angle on global and local reaction times depends on the set of visual angles presented. *Perception & Psychophysics*, 47(5), 489–96. doi: 10.3758/BF03208182
- Lambon Ralph, M. A. & Patterson, K. (2007). Acquired disorders of reading. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 413–430). Oxford, England: Blackwell Publishing. doi: 10.1002/9780470757642.ch22
- Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance*, 21(3), 451–468. doi: 10.1037/0096-1523.21.3.451
- Leat, S. J., Li, W. & Epp, K. (1999). Crowding in central and eccentric vision: The effects of contour interaction and attention. *Investigative Ophthalmology*

- Visual Science*, 40(2), 504–12.
- Legge, G. E., Pelli, D. G., Rubin, G. S. & Schleske, M. M. (1985). Psychophysics of reading - I. Normal vision. *Vision Research*, 25(2), 239–252. doi: 10.1016/0042-6989(85)90117-8
- Lehmkuhle, S., Garzia, R. P., Turner, L., Hash, T. & Baro, J. A. (1993). A defective visual pathway in children with reading disability. *The New England Journal of Medicine*, 328(14), 989–96. doi: 10.1056/NEJM199304083281402
- Liberman, I. Y. & Shankweiler, D. (1979). Speech, the alphabet and teaching to read. In L. Resnick & P. Weaver (Eds.), *Theory and practice of early reading* (2nd ed., pp. 109–132). Hillsdale, NJ: Erlbaum.
- Livingstone, M. S., Rosen, G. D., Drislane, F. W. & Galaburda, A. M. (1991). Physiological and anatomical evidence for a magnocellular defect in developmental dyslexia. *Proceedings of the National Academy of Sciences*, 88(18), 7943–7947. doi: 10.1073/pnas.88.18.7943
- Lovegrove, W., Martin, F. & Slaghuis, W. (1986). A theoretical and experimental case for a visual deficit in specific reading disability. *Cognitive Neuropsychology*, 3(2), 225–267. doi: 10.1080/02643298608252677
- Luna, D., Marcos-ruiz, R. & Merino, J. M. (1995). Selective attention to global and local information: Effects of visual angle, exposure duration, and eccentricity on processing dominance. *Visual Cognition*, 2(2-3), 183–200. doi: 10.1080/13506289508401730
- Luna, D., Merino, J. M. & Marcos-Ruiz, R. (1990). Processing dominance of global and local information in visual patterns. *Acta Psychologica*, 73(2), 131–143. doi: 10.1016/0001-6918(90)90075-Q
- Lux, S., Marshall, J. C., Ritzl, A., Weiss, P. H., Pietrzyk, U., Shah, N. J., . . . Fink, G. R. (2004). A functional magnetic resonance imaging study of local/global processing with stimulus presentation in the peripheral visual hemifields. *Neuroscience*, 124(1), 113–120. doi: 10.1016/j.neuroscience.2003.10.044
- Lyon, G. R., Fletcher, J. M. & Barnes, M. (2002). Learning disabilities. In E. J. Marsh & R. A. Barkley (Eds.), *Child psychopathology* (2nd ed., pp. 520–588). New York: Guilford Press.
- Marsh, G., Desberg, P. & Cooper, J. (1977). Developmental changes in reading

- strategies. *Journal of Reading Behavior*, 9(4), 391–394.
- Marsh, G., Friedman, M., Desberg, P. & Saterdahl, K. (1981). Comparison of reading and spelling strategies in normal and reading disabled children. In M. P. Friedman, J. P. Das & N. O'Connor (Eds.), *Intelligence and learning* (pp. 363–367). New York, NY: Springer US. doi: 10.1007/978-1-4684-1083-9_33
- Marshall, J. C. & Newcombe, F. (1973). Patterns of paralexia: A psycholinguistic approach. *Journal of Psycholinguistic Research*, 2(3), 175–199. doi: 10.1007/BF01067101
- Martin, M. (1978). Speech recoding in silent reading. *Memory & Cognition*, 6(2), 108–114. doi: 10.3758/BF03197435
- Martin, M. (1979). Local and global processing: The role of sparsity. *Memory & Cognition*, 7(6), 476–484. doi: 10.3758/BF03198264
- Mason, M. (1975). Reading ability and letter search time: Effects of orthographic structure defined by single-letter positional frequency. *Journal of Experimental Psychology: General*, 104(2), 146–166. doi: 10.1037/0096-3445.104.2.146
- Mason, M. (1982). Recognition time for letters and nonletters: Effects of serial position, array size, and processing order. *Journal of Experimental Psychology: Human Perception and Performance*, 8(5), 724–738. doi: 10.1037/0096-1523.8.5.724
- Mason, M. & Katz, L. (1976). Visual processing of nonlinguistic strings: Redundancy effects and reading ability. *Journal of Experimental Psychology: General*, 105(4), 338–348. doi: 10.1037/0096-3445.105.4.338
- Masonheimer, P., Drum, P. & Ehri, L. C. (1984). Does environmental print identification lead children into word reading? *Journal of Literacy Research*, 16(4), 257–271. doi: 10.1080/10862968409547520
- Massaro, D. W. (1998). Models for reading letters and words. In D. Scarborough & S. Sternberg (Eds.), *Methods, models and conceptual issues* (2nd ed.). Cambridge, MA; London, England: MIT Press.
- Mattingly, I. G. (1984). Reading, linguistic awareness, and language acquisition. In J. Downing & R. Valtin (Eds.), *Reading, linguistic awareness, and language acquisition* (pp. 9–25). New York, NY: Springer New York. doi: 10.1007/978-

1-4613-8248-5_2

- Maurer, U., Brem, S., Bucher, K. & Brandeis, D. (2005). Emerging neurophysiological specialization for letter strings. *Journal of Cognitive Neuroscience*, *17*(10), 1532–52. doi: 10.1162/089892905774597218
- Maurer, U., Brem, S., Kranz, F., Bucher, K., Benz, R., Halder, P., . . . Brandeis, D. (2006). Coarse neural tuning for print peaks when children learn to read. *NeuroImage*, *33*(2), 749–58. doi: 10.1016/j.neuroimage.2006.06.025
- McBride-Chang, C. (1996). Models of speech perception and phonological processing in reading. *Child Development*, *67*(4), 1836–1856. doi: 10.2307/1131735
- McBride-Chang, C. (1999). The ABCs of the ABCs: The development of letter-name and letter-sound knowledge. *Merrill - Palmer Quarterly*, *45*(2), 285–309.
- McCandliss, B. D., Cohen, L. & Dehaene, S. (2003). The visual word form area: Expertise for reading in the fusiform gyrus. *Trends in Cognitive Sciences*, *7*(7), 293–299. doi: 10.1016/S1364-6613(03)00134-7
- McCann, R. S. & Besner, D. (1987). Reading pseudohomophones: Implications for models of pronunciation assembly and the locus of word-frequency effects in naming. *Journal of Experimental Psychology: Human Perception and Performance*, *13*(1), 14–24. doi: 10.1037/0096-1523.13.1.14
- McClelland, J. L. (1976). Preliminary letter identification in the perception of words and nonwords. *Journal of Experimental Psychology: Human Perception and Performance*, *2*(1), 80–91. doi: 10.1037/0096-1523.2.1.80
- McCusker, L. X., Hillinger, M. L. & Bias, R. G. (1981). Phonological recoding and reading. *Psychological Bulletin*, *89*(2), 217–245. doi: 10.1037/0033-2909.89.2.217
- Mewhort, D. J. (1974). Accuracy and order of report in tachistoscopic identification. *Canadian Journal of Psychology*, *28*, 383–398. doi: 10.1037/h0082004
- Meyer, D. E., Schvaneveldt, R. W. & Ruddy, M. G. (1974). Functions of graphemic and phonemic codes in visual word-recognition. *Memory & Cognition*, *2*(2), 309–21. doi: 10.3758/BF03209002
- Miller, J. (1991). The flanker compatibility effect as a function of visual angle, attentional focus, visual transients, and perceptual load: A search for

- boundary conditions. *Perception & Psychophysics*, 49(3), 270–288. doi: 10.3758/BF03214311
- Moll, K. & Landerl, K. (2014). *SLRT-II* (2nd ed.). Bern: Huber, Hogrefe.
- Morris, R. D., Stuebing, K. K., Fletcher, J. M., Shaywitz, S. E., Lyon, G. R., Shankweiler, D. P., . . . Shaywitz, B. A. (1998). Subtypes of reading disability: Variability around a phonological core. *Journal of Educational Psychology*, 90(3), 347–373. doi: 10.1037/0022-0663.90.3.347
- Morton, J. (1969). Interaction of information in word recognition. *Psychological Review*, 76(2), 165–178. doi: 10.1037/h0027366
- Morton, J. (1980). The logogen model and orthographic structure. In U. Frith (Ed.), *Cognitive processes in spelling* (pp. 117–134). London: Academic Press.
- Näslund, J. C. & Schneider, W. (1996). Kindergarten letter knowledge, phonological skills, and memory processes: Relative effects on early literacy. *Journal of Experimental Child Psychology*, 62(1), 30–59. doi: 10.1006/jecp.1996.0021
- Navon, D. (1977). Forest before trees: The precedence of global features in visual perception. *Cognitive Psychology*, 9(3), 353–383. doi: 10.1016/0010-0285(77)90012-3
- Navon, D. (1981). The forest revisited: More on global precedence. *Psychological Research*, 43(1), 1–32. doi: 10.1007/BF00309635
- Navon, D. (2003). What does a compound letter tell the psychologist’s mind? *Acta Psychologica*, 114(3), 273–309. doi: 10.1016/j.actpsy.2003.06.002
- Navon, D. & Norman, J. (1983). Does global precedence really depend on visual angle? *Journal of Experimental Psychology: Human Perception and Performance*, 9(6), 955–965. doi: 10.1037/0096-1523.9.6.955
- New, B., Ferrand, L., Pallier, C. & Brysbaert, M. (2006). Reexamining the word length effect in visual word recognition: New evidence from the English Lexicon Project. *Psychonomic Bulletin & Review*, 13(1), 45–52. doi: 10.3758/BF03193811
- Nicolson, R. I. & Fawcett, A. J. (2011). Dyslexia, dysgraphia, procedural learning and the cerebellum. *Cortex*, 47(1), 117–127. doi: 10.1016/j.cortex.2009.08.016

- Oden, G. C. (1979). A fuzzy logical model of letter identification. *Journal of Experimental Psychology: Human Perception and Performance*, 5(2), 336–352. doi: 10.1037/0096-1523.5.2.336
- Orton, S. T. (1925). "Word-Blindness" in school children. *Archives of Neurology and Psychiatry*, 14(5), 581. doi: 10.1001/archneur-psyc.1925.02200170002001
- Paap, K. R. & Noel, R. W. (1991). Dual-route models of print to sound: Still a good horse race. *Psychological Research*, 53(1), 13–24. doi: 10.1007/BF00867328
- Patterson, K. E. & Hodges, J. R. (1992). Deterioration of word meaning: Implications for reading. *Neuropsychologia*, 30(12), 1025–1040. doi: 10.1016/0028-3932(92)90096-5
- Patterson, K. E. & Lambon Ralph, M. A. (1999). Selective disorders of reading? *Current Opinion in Neurobiology*, 9(2), 235–239. doi: 10.1016/S0959-4388(99)80033-6
- Paulesu, E., McCrory, E., Fazio, F., Menoncello, L., Brunswick, N., Cappa, S. F., ... Frith, U. (2000). A cultural effect on brain function. *Nature Neuroscience*, 3(1), 91–96. doi: 10.1038/71163
- Pegado, F., Nakamura, K., Braga, L. W., Ventura, P., Nunes Filho, G., Pallier, C., ... Dehaene, S. (2014). Literacy breaks mirror invariance for visual stimuli: A behavioral study with adult illiterates. *Journal of Experimental Psychology: General*, 143(2), 887–94. doi: 10.1037/a0033198
- Pegado, F., Nakamura, K., Cohen, L. & Dehaene, S. (2011). Breaking the symmetry: Mirror discrimination for single letters but not for pictures in the visual word form area. *NeuroImage*, 55(2), 742–749. doi: 10.1016/j.neuroimage.2010.11.043
- Perea, M., Moret-Tatay, C. & Panadero, V. (2011). Suppression of mirror generalization for reversible letters: Evidence from masked priming. *Journal of Memory and Language*, 65(3), 237–246. doi: 10.1016/j.jml.2011.04.005
- Peressotti, F., Rumiati, R., Nicoletti, R. & Job, R. (1991). New evidence for the perceptual precedence of global information. *Acta Psychologica*, 77(1), 35–46. doi: 10.1016/0001-6918(91)90063-6
- Pitchford, N. J., Ledgeway, T. & Masterson, J. (2008). Effect of orthographic

- processes on letter position encoding. *Journal of Research in Reading*, 31(1), 97–116. doi: 10.1111/j.1467-9817.2007.00363.x
- Plaut, D. C. (1996). Relearning after damage in connectionist networks: Toward a theory of rehabilitation. *Brain and Language*, 52(1), 25–82. doi: 10.1006/brln.1996.0004
- Plomp, G., van Leeuwen, C. & Ioannides, A. A. (2010). Functional specialization and dynamic resource allocation in visual cortex. *Human Brain Mapping*, 31(1), 1–13. doi: 10.1002/hbm.20840
- Poirel, N., Leroux, E., Pineau, A., Houdé, O. & Simon, G. (2014). Changes in cortical thickness in 6-year-old children open their mind to a global vision of the world. *BioMed Research International*. doi: 10.1155/2014/362349
- Poirel, N., Pineau, A., Jobard, G. & Mellet, E. (2008). Seeing the forest before the trees depends on individual field-dependency characteristics. *Experimental Psychology*, 55(5), 328–333. doi: 10.1027/1618-3169.55.5.328
- Poirel, N., Pineau, A. & Mellet, E. (2006). Implicit identification of irrelevant local objects interacts with global/local processing of hierarchical stimuli. *Acta Psychologica*, 122(3), 321–336. doi: 10.1016/j.actpsy.2005.12.010
- Poirel, N., Pineau, A. & Mellet, E. (2008). What does the nature of the stimuli tell us about the Global Precedence Effect? *Acta Psychologica*, 127(1), 1–11. doi: 10.1016/j.actpsy.2006.12.001
- Pollatsek, A. (1993). Eye movements in reading. In D. M. Willows, R. S. Kruk & E. Corcos (Eds.), *Visual processes in reading and reading disabilities* (pp. 191–214). Hillsdale, NJ: Lawrence Erlbaum Associates. doi: 10.1016/B0-08-043076-7/01555-2
- Pomerantz, J. R. (1983). Global and local precedence: Selective attention in form and motion perception. *Journal of Experimental Psychology: General*, 112(4), 516–540. doi: 10.1037/0096-3445.112.4.516
- Pugh, K. R., Einar Mencl, W., Jenner, A. R., Katz, L., Frost, S. J., Lee Ren, J., ... Laboratories, H. (2000). Functional neuroimaging studies of reading and reading disability (developmental dyslexia). *Mental Retardation and Developmental Disabilities Research Reviews*, 6(3), 207–213. doi: 10.1002/1098-2779(2000)6:3<207::AID-MRDDD>3.0.CO;2-P
- Rastle, K. & Coltheart, M. (1999a). Lexical and nonlexical phonological priming

- in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance*, 25(2), 461–481. doi: 10.1037/0096-1523.25.2.461
- Rastle, K. & Coltheart, M. (1999b). Serial and strategic effects in reading aloud. *Journal of Experimental Psychology: Human Perception and Performance*, 25(2), 482–503. doi: 10.1037/0096-1523.25.2.482
- Rayner, K., Balota, D. A. & Pollatsek, A. (1986). Against parafoveal semantic pre-processing during eye fixations in reading. *Canadian Journal of Psychology*, 40(4), 473–483. doi: 10.1037/h0080111
- Richardson, U., Thomson, J. M., Scott, S. K. & Goswami, U. (2004). Auditory processing skills and phonological representation in dyslexic children. *Dyslexia*, 10(3), 215–33. doi: 10.1002/dys.276
- Roberts, T. A. (2003). Effects of alphabet-letter instruction on young children's word recognition. *Journal of Educational Psychology*, 95(1), 41–51. doi: 10.1037/0022-0663.95.1.41
- Rueckl, J. G., Suzuki, S. & Yeh, S.-L. (1991). On the locus of redundancy effects in a letter-detection task. *Perception & Psychophysics*, 49(5), 412–421. doi: 10.3758/BF03212175
- Rusiak, P., Lachmann, T., Jaskowski, P. & van Leeuwen, C. (2007). Mental rotation of letters and shapes in developmental dyslexia. *Perception*, 36(4), 617–631. doi: 10.1068/p5644
- Samuels, S. J. & Kamil, M. L. (1984). Models of the reading process. In P. D. Pearson, R. Barr, M. L. Kamil & P. Mosenthal (Eds.), *Handbook of reading research* (pp. 185–224). Mahwah, NJ; London, UK: Lawrence Erlbaum Associates.
- Samuels, S. J., LaBerge, D. & Bremer, C. D. (1978). Units of word recognition: Evidence for developmental changes. *Journal of Verbal Learning and Verbal Behavior*, 17(6), 715–720. doi: 10.1016/S0022-5371(78)90433-4
- Sandak, R., Mencl, W. E., Frost, S. J. & Pugh, K. R. (2004). The neurobiological basis of skilled and impaired reading: Recent findings and new directions. *Scientific Studies of Reading*, 8(3), 273–292. doi: 10.1207/s1532799xssr0803_6
- Sanders, A. F. (1970, jan). Some aspects of the selective process in the functional visual field. *Ergonomics*, 13(1), 101–117. doi: 10.1080/00140137008931124

- Sanders, A. F. & Lamers, J. M. (2002). The Eriksen flanker effect revisited. *Acta Psychologica*, 109(1), 41–56. doi: 10.1016/S0001-6918(01)00048-8
- Scheerer-Neumann, G. (2006). Entwicklung der basalen Lesefähigkeit. In U. Bredel (Ed.), *Didaktik der deutschen Sprache* (pp. 513–524). Paderborn: Schöningh UTB.
- Schlaggar, B. L., Brown, T. T., Lugar, H. M., Visscher, K. M., Miezin, F. M. & Petersen, S. E. (2002). Functional neuroanatomical differences between adults and school-age children in the processing of single words. *Science*, 296(5572), 1476–9. doi: 10.1126/science.1069464
- Schlaggar, B. L. & McCandliss, B. D. (2007). Development of neural systems for reading. *Annual Review of Neuroscience*, 30, 475–503. doi: 10.1146/annurev.neuro.28.061604.135645
- Seidenberg, M. S., Petersen, A., Macdonald, M. C. & Plaut, D. C. (1996). Pseudohomophone effects and models of word recognition. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, 22(1), 48–62. doi: 10.1037/0278-7393.22.1.48
- Seidenberg, M. S., Waters, G. S., Barnes, M. A. & Tanenhaus, M. K. (1984). When does irregular spelling or pronunciation influence word recognition? *Journal of Verbal Learning and Verbal Behavior*, 23(3), 383–404. doi: 10.1016/S0022-5371(84)90270-6
- Seymour, P. H. K. & Evans, H. M. (1993). The visual (orthographic) processor and developmental dyslexia. In D. M. Willows, R. S. Kruk & E. Corcos (Eds.), *Visual processes in reading and reading disabilities* (pp. 347–376). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Shallice, T., Warrington, E. K. & McCarthy, R. (1983). Reading without semantics. *The Quarterly Journal of Experimental Psychology: Section A: Human Experimental Psychology*, 35A(1), 111–138. doi: 10.1080/14640748308402120
- Shaywitz, B. A., Shaywitz, S. E., Pugh, K. R., Mencl, W. E., Fulbright, R. K., Skudlarski, P., ... Gore, J. C. (2002). Disruption of posterior brain systems for reading in children with developmental dyslexia. *Biological Psychiatry*, 52(2), 101–110. doi: 10.1016/S0006-3223(02)01365-3
- Shaywitz, S. E., Escobar, M. D., Shaywitz, B. A., Fletcher, J. M. & Makuch, R.

- (1992). Evidence that dyslexia may represent the lower tail of a normal distribution of reading ability. *The New England Journal of Medicine*, *326*(3), 145–50. doi: 10.1056/NEJM199201163260301
- Shaywitz, S. E. & Shaywitz, B. A. (2008). Paying attention to reading: The neurobiology of reading and dyslexia. *Development and Psychopathology*, *20*(4), 1329–1349. doi: 10.1017/S0954579408000631
- Slaghuis, W. L. & Ryan, J. F. (1999). Spatio-temporal contrast sensitivity, coherent motion, and visible persistence in developmental dyslexia. *Vision Research*, *39*(3), 651–68. doi: 10.1016/S0042-6989(98)00151-5
- Snow, C. E., Barnes, W. S., Chandler, J., Goodman, I. F. & Hemphill, L. (1991). *Unfulfilled expectations: Home and school influences on literacy*. Cambridge, MA: Harvard University Press.
- Snowling, M. J. (1980). The development of grapheme-phoneme correspondence in normal and dyslexic readers. *Journal of Experimental Child Psychology*, *29*(2), 294–305. doi: 10.1016/0022-0965(80)90021-1
- Snowling, M. J. (2000). *Dyslexia* (2nd ed.). Oxford, UK: Blackwell Publishing.
- Snowling, M. J. (2001). From language to reading and dyslexia. *Dyslexia*, *7*(1), 37–46. doi: 10.1002/dys.185
- Snowling, M. J. & Hulme, C. (Eds.). (2007). *The science of reading: A handbook*. Oxford, UK: Blackwell Publishing. doi: 10.1002/9780470757642
- Sperling, G. (1960). The information available in brief visual presentations. *Psychological Monographs: General and Applied*, *74*(11), 1–29. doi: 10.1037/h0093759
- Stanovich, K. E. (1982a). Individual differences in the cognitive processes of reading: II. Text-level processes. *Journal of Learning Disabilities*, *15*(9), 549–554. doi: 10.1177/002221948201500908
- Stanovich, K. E. (1982b). Individual differences in the cognitive processes of reading: I. Word decoding. *Journal of Learning Disabilities*, *15*(8), 485–493. doi: 10.1177/002221948201500809
- Stein, J. (2002). The neurobiology of reading difficulties. In E. Witruk, A. D. Friederici & T. Lachmann (Eds.), *Basic functions of language, reading and reading disability* (pp. 199–211). Boston, MA: Springer US. doi: 10.1007/978-1-4615-1011-6_12

- Stein, J. (2012). The neurobiological basis of dyslexia: The magnocellular theory. In M. Faust (Ed.), *The handbook of the neuropsychology of language* (pp. 938–962). Oxford, UK: Blackwell Publishing. doi: 10.1002/9781118432501.ch45
- Stein, J., Talcott, J. & Witton, C. (2001). The sensorimotor basis of developmental dyslexia. In A. Fawcett (Ed.), *Dyslexia: Theory and good practice* (pp. 65–88). London: Whurr.
- Steinbrink, C. (2006). Was reimt sich auf Maus? Phonologische Bewusstheit: Eine Grundlage für richtiges Lesen und Schreiben. *Grundschule*, 5, 51–53.
- Steinbrink, C., Groth, K., Lachmann, T. & Riecker, A. (2012). Neural correlates of temporal auditory processing in developmental dyslexia during German vowel length discrimination: An fMRI study. *Brain and Language*, 121(1), 1–11. doi: 10.1016/j.bandl.2011.12.003
- Steinbrink, C. & Lachmann, T. (2014). *Lese-Rechtschreibstörung*. Berlin, Heidelberg, Germany: Springer. doi: 10.1007/978-3-642-41842-6
- Steinbrink, C., Schwanda, S., Klatte, M. & Lachmann, T. (2010). Sagen Wahrnehmungsleistungen zu Beginn der Schulzeit den Lese-Rechtschreiberfolg in Klasse 1 und 2 voraus? *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, 42(4), 188–200. doi: 10.1026/0049-8637/a000023
- Stevens, M. & Grainger, J. (2003). Letter visibility and the viewing position effect in visual word recognition. *Perception & Psychophysics*, 65(1), 133–51. doi: 10.3758/BF03194790
- Tabors, P. O. & Snow, C. T. (2001). Young bilingual children and early literacy development. In S. B. Neuman & D. K. Dickinson (Eds.), *Handbook of early literacy research* (pp. 159–178). New York, NY: Guilford Press.
- Taft, M. & Russell, B. (1992). Pseudohomophone naming and the word frequency effect. *The Quarterly Journal of Experimental Psychology: Section A: Human Experimental Psychology*, 45(1), 51–71. doi: 10.1080/14640749208401315
- Talcott, J. B. & Witton, C. (2002). A sensory linguistic approach to the development of normal and dysfunctional reading skills. In E. Witruk, A. D. Friederici & T. Lachmann (Eds.), *Basic functions of language, reading and reading*

- disability* (pp. 213–240). Boston, MA: Springer US. doi: 10.1007/978-1-4615-1011-6_13
- Taraban, R. & McClelland, J. L. (1987). Conspiracy effects in word recognition. *Journal of Memory and Language*, *26*(6), 608–631. doi: 10.1016/0749-596X(87)90105-7
- Toet, A. & Levi, D. M. (1992). The two-dimensional shape of spatial interaction zones in the parafovea. *Vision Research*, *32*(7), 1349–1357. doi: 10.1016/0042-6989(92)90227-A
- Torgesen, J. K. & Houck, D. G. (1980). Processing deficiencies of learning-disabled children who perform poorly on the Digit Span Test. *Journal of Educational Psychology*, *72*(2), 141–160. doi: 10.1037/0022-0663.72.2.141
- Treiman, R. (1992). The role of intrasyllabic units in learning to read and spell. In P. B. Gough, L. C. Ehri & R. Treiman (Eds.), *Reading acquisition* (pp. 65–106). Hillsdale, NJ: Lawrence Erlbaum Associates.
- Treisman, A. M. & Gelade, G. (1980). A feature-integration theory of attention. *Cognitive Psychology*, *12*(1), 97–136. doi: 10.1016/0010-0285(80)90005-5
- Turkeltaub, P. E., Gareau, L., Flowers, D. L., Zeffiro, T. A. & Eden, G. F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience*, *6*(7), 767–773. doi: 10.1038/nm1065
- Tydgat, I. & Grainger, J. (2009). Serial position effects in the identification of letters, digits, and symbols. *Journal of Experimental Psychology: Human Perception and Performance*, *35*(2), 480–498. doi: 10.1037/a0013027
- van den Boer, M. & de Jong, P. F. (2015). Parallel and serial reading processes in children’s word and nonword reading. *Journal of Educational Psychology*, *107*(1), 141–151. doi: 10.1037/a0037101
- van Leeuwen, C. & Bakker, L. (1995). Stroop can occur without Garner interference: Strategic and mandatory influences in multidimensional stimuli. *Perception & Psychophysics*, *57*(3), 379–392. doi: 10.3758/BF03213062
- van Leeuwen, C. & Lachmann, T. (2004). Negative and positive congruence effects in letters and shapes. *Perception & Psychophysics*, *66*(6), 908–925. doi: 10.3758/BF03194984
- Vellutino, F. R. (1979). *Dyslexia: Theory and research*. Cambridge, MA: MIT Press.

- Vellutino, F. R. & Fletcher, J. M. (2007). Developmental dyslexia. In M. J. Snowling & C. Hulme (Eds.), *The science of reading: A handbook* (pp. 362–378). Oxford, UK: Blackwell Publishing. doi: 110.1002/9780470757642.ch19
- Venezky, R. L. (1970). *The structure of English orthography*. Berlin, New York: De Gruyter. doi: 10.1515/9783110804478
- Volberg, G. & Hübner, R. (2004). On the role of response conflicts and stimulus position for hemispheric differences in global/local processing: An ERP study. *Neuropsychologia*, 42(13), 1805–1813. doi: 10.1016/j.neuropsychologia.2004.04.017
- Volberg, G. & Hübner, R. (2007). Do the hemispheres differ in their preparation for global/local processing? *Experimental Brain Research*, 176(3), 525–531. doi: 10.1007/s00221-006-0796-9
- von Goldammer, A., Mähler, C., Bockmann, A.-K. & Hasselhorn, M. (2010). Vorhersage früher Schriftsprachleistungen aus vorschulischen Kompetenzen der Sprache und der phonologischen Informationsverarbeitung. *Zeitschrift für Entwicklungspsychologie und Pädagogische Psychologie*, 42(1), 48–56. doi: 10.1026/0049-8637/a000005
- von Károlyi, C., Winner, E., Gray, W. & Sherman, G. F. (2003). Dyslexia linked to talent: Global visual-spatial ability. *Brain and Language*, 85(3), 427–431. doi: 10.1016/S0093-934X(03)00052-X
- Wagemans, J., Elder, J. H., Kubovy, M., Palmer, S. E., Peterson, M. A., Singh, M. & von der Heydt, R. (2012). A century of Gestalt psychology in visual perception: I. Perceptual grouping and figureground organization. *Psychological Bulletin*, 138(6), 1172–1217. doi: 10.1037/a0029333
- Wagner, R. K. & Torgesen, J. K. (1987). The nature of phonological processing and its causal role in the acquisition of reading skills. *Psychological Bulletin*, 101(2), 192–212. doi: 10.1037/0033-2909.101.2.192
- Wagner, R. K., Torgesen, J. K. & Rashotte, C. a. (1994). Development of reading-related phonological processing abilities: New evidence of bidirectional causality from a latent variable longitudinal study. *Developmental Psychology*, 30(1), 73–87. doi: 10.1037/0012-1649.30.1.73
- Wagner, R. K., Torgesen, J. K., Rashotte, C. A., Hecht, S. A., Barker, T. A., Burgess, S. R., ... Garon, T. (1997). Changing relations between phono-

- logical processing abilities and word-level reading as children develop from beginning to skilled readers: A 5-year longitudinal study. *Developmental Psychology*, 33(3), 468–479. doi: 10.1037/0012-1649.33.3.468
- Wagstaffe, J., Pitchford, N. & Ledgeway, T. (2005). Does central fixation account for medial letter facilitation in visual search? *Perception*, 34(Suppl.), 150. doi: 10.1177/03010066050340S101
- Watson, C. S., Kidd, G. R., Homer, D. G., Connell, P. J., Lowther, A., Ed-dins, D. A., ... Watson, B. U. (2003). Sensory, cognitive, and linguistic factors in the early academic performance of elementary school children: The Benton-IU project. *Journal of Learning Disabilities*, 36(2), 165–197. doi: 10.1177/002221940303600209
- Weiß, R. H. & Weiß, B. (2006). *Grundintelligenztest Skala 2* (Revision ed.). Göttingen: Hogrefe.
- White, S. J., Johnson, R. L., Liversedge, S. P. & Rayner, K. (2008). Eye movements when reading transposed text: The importance of word-beginning letters. *Journal of Experimental Psychology: Human Perception and Performance*, 34(5), 1261–1276. doi: 10.1037/0096-1523.34.5.1261
- Wimmer, H. & Hummer, P. (1990). How German-speaking first graders read and spell: Doubts on the importance of the logographic stage. *Applied Psycholinguistics*, 11(4), 349–368. doi: 10.1017/S0142716400009620
- Wimmer, H., Landerl, K., Linortner, R. & Hummer, P. (1991). The relationship of phonemic awareness to reading acquisition: More consequence than precondition but still important. *Cognition*, 40(3), 219–249. doi: 10.1016/0010-0277(91)90026-Z
- Wimmer, H. & Mayringer, H. (2014). *Salzburger Lese-Screening für die Schulstufen 2-9 (SLS 2-9)*. Bern: Huber.
- Wolf, M. (1986). Rapid alternating stimulus naming in the developmental dyslexias. *Brain and Language*, 27(2), 360–379. doi: 10.1016/0093-934X(86)90025-8
- Wolf, M., Bowers, P. G. & Biddle, K. (2000). Naming-speed processes, timing, and reading: A conceptual review. *Journal of Learning Disabilities*, 33(4), 387–407. doi: 10.1177/002221940003300409
- Wolf, M., Pfeil, C., Lotz, R. & Biddle, K. (1994). Towards a more universal

- understanding of the developmental dyslexia: The contribution of orthographic factors. In V. Berninger (Ed.), *The varieties of orthographic knowledge* (1st ed., pp. 137–171). Dordrecht, Netherlands: Springer Netherlands. doi: 10.1007/978-94-017-3492-9_5
- Wolf, M. & Wiese, M. (2009). *Das lesende Gehirn: Wie der Mensch zum Lesen kam und - was es in unseren Köpfen bewirkt*. Heidelberg: Spektrum Akademischer Verlag.
- World Health Organization. (1992). F81.0 Specific reading disorder. In *The ICD-10 classification of mental and behavioural disorders - Clinical descriptions and diagnostic guidelines* (p. 245). Geneva.
- Ziegler, J. C., Pech-Georgel, C., Dufau, S. & Grainger, J. (2010). Rapid processing of letters, digits and symbols: What purely visual-attentional deficit in developmental dyslexia? *Developmental Science*, 13(4), F8–F14. doi: 10.1111/j.1467-7687.2010.00983.x
- Ziegler, J. C., Perry, C. & Coltheart, M. (2000). The DRC model of visual word recognition and reading aloud: An extension to German. *European Journal of Cognitive Psychology*, 12(3), 413–430. doi: 10.1080/09541440050114570

Acknowledgement

This work was submitted to the Faculty of Social Science of the University of Kaiserslautern in fulfillment of the requirements for the degree of Doctor of Philosophy. Therefore, it includes the experiments, which I conducted during the period of my PhD study.

During this time also some manuscripts concerning the studies were written and submitted. Hence, some parts of this work are similar to these manuscripts. Parts of the short summary and introduction concerning the Global Precedence Effect (Chapter 2.5) are published in Lachmann et al. (2014) or were part of a manuscript sent to *Acta Psychologica*. The same holds for the theoretical and experimental parts of Study 1 (Chapter 4.3) and Study 2 (Chapter 5). Although, the studies were mainly planned and conducted by myself, there were several people which helped me with the design, data acquisition and interpretation of the results.

At this point, I would like to thank these people, which helped me to conduct and finish this thesis. First I would like to thank my supervisor Thomas Lachmann, who offered me the chance to write this PhD thesis. Thank you for your confidence in my skills, for your support and your many ideas, which helped me to answer my research questions. Also, many thanks to Cees van Leeuwen for your inspiring comments to my research project and your hints, how to describe my research results. I have learned a lot about rules of scientific writing during our common time writing the two manuscripts. Furthermore, I would like to thank Max Wolkersdorfer and Larissa Leist, for collecting the data of two experiments (Chapter 4.2 and 7) and all the teachers and children, for participating in my school study (Chapter 6) and participants of all studies.

But moreover, I would like to thank my girlfriend Tina Weis. Thank you, for all the time of proofreading. Thank you, for all the time in which you helped me

with so many problems during this thesis. Thank you, for all the time, motivating me to keep going to finish this thesis. And thank you for standing by my side.

A. Curriculum Vitae

Academic experiences

- since 11/2016 Research scientist / Lecturer
Institute for Educational Science, Faculty I - Educational and Social Sciences, Carl von Ossietzky University Oldenburg
- 05/2013 – 12/2016 Research scientist / PhD Student
Department for Cognitive and Developmental Psychology, Faculty for Social Sciences, University of Kaiserslautern
- 04/2013 Master of Education and first state examination
Faculty for Chemistry, University of Kaiserslautern
- 03/2011 Bachelor of Education
Faculty for Social Sciences, University of Kaiserslautern
- 10/2007 – 04/2013 Studies of chemistry, physics and educational sciences for grammar school teaching
University of Kaiserslautern

Publications

Journal Publikationen

- Schmitt, A., Lachmann, T. & van Leeuwen, C. (under review). Letters will be letters: On the impossibility of converting non-letter-shapes. *Acta Psychologica*

Lachmann, T., **Schmitt, A.**, Braet, W. & van Leeuwen, C. (2014). Letters in the forest: Global precedence effect disappears for letters but not for non-letters under reading-like conditions. *Front. Psychol.* 5:705. doi: 10.3389/fpsyg.2014.00705

Book chapters

Aykat, L., Brixius, S., **Schmitt, A.** & Zimmermann, S. (2012). Steuergruppe - Die Spinne im Netz. In: Arnold, R. & Prescher, T. (Eds.), *Schule als Organisation entwickeln: Praxis der Schulentwicklung für Lehrkräfte* (pp.34-52). Pädagogische Materialien der Technischen Universität Kaiserslautern, Kaiserslautern, Germany

Talks at conferences

Schmitt, A., & Lachmann, T. (2016, sept). Navon figures give evidence for a lack of automatized letter processing strategies in children with developmental dyslexia. Talk at the 50. Kongress der Deutschen Gesellschaft für Psychologie, Leipzig, Germany.

Schmitt, A., & Lachmann, T. (2016, aug). Different processing of Navon figures in children with normal reading skills compared to children with poor reading abilities. Talk at the 32. Annual Meeting of the International Society for Psychophysics (Fechner Day), Moscow, Russia.

Schmitt, A., & Lachmann, T. (2016, mar). Still letters in the forest: Global precedence effect for non-letters keeps robust even after phonological association training. Talk at the 58. Tagung experimentell arbeitender Psychologen, Heidelberg, Germany.

Schmitt, A. & Lachmann, T. (2015, nov). Autumn leaves - the trees changes, but the forest remains: Global precedence effect for non-letters keeps robust even after phonological association training. Talk at the Herbstkolloquium Kognitionspsychologie, Kaiserslautern, Germany.

Schmitt, A. & Lachmann, T. (2015, aug). Letters in the forest: Global precedence effect disappears for letters but not for non-letters under reading-like conditions even after a phonological association training. Talk at the 31.

Annual Meeting of the International Society for Psychophysics (Fechner Day), Québec, Canada.

Schmitt, A., Braet, W., van Leeuwen, C. & Lachmann, T. (2015, mar). Letters in the forest: Global precedence effect disappears for letters but not for non-letters under reading-like conditions. Talk at the 57. Tagung experimentell arbeitender Psychologen, Hildesheim, Germany.

Conference proceeding

Schmitt, A., & Lachmann, T. (2016). Different processing of Navon figures in children with normal reading skills compared to children with poor reading abilities. In: Skotnikova, I., Korolkova, O., Blinnikova, I., Doubrovski, V., Shendyapin, V. & Volkova, N. (Eds.), Fechner Day 2016 - Proceedings of the 32nd Annual Meeting of the International Society for Psychophysics. International Society for Psychophysics, Moscow, Russia .

Schmitt, A., & Lachmann, T. (2015). Letters in the forest: Global precedence effect disappears for letters but not for non-letters under reading-like conditions. In: Grondin, S. & Laflamme, V. (Eds.), Fechner Day 2015 - Proceedings of the 31st Annual Meeting of the International Society for Psychophysics. International Society for Psychophysics, Québec, Canada.

Poster

Schmitt, A., & Lachmann, T. (2015, oct). Still letters in the forest: Global precedence effect for non-letters keeps robust even after phonological association training, Poster at the International Workshop - Reading in the forest, Annweiler, Germany

Schmitt, A., & Lachmann, T. (2015, aug). Letters in the forest: Global precedence effect disappears for letters but not for non-letters under reading-like conditions. Poster at the European Conference on Visual Perception, Liverpool, GB