PROCESSING IN THE PERCEPTUAL SPAN: INVESTIGATIONS WITH THE N+2-BOUNDARY PARADIGM

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ZUSAMMENFASSUNG

Die kognitive Psychologie beschäftigt sich traditionell mit dem Zusammenspiel von Wahrnehmung, Kognition und Verhaltenssteuerung. Die Untersuchung von Blickbewegungen beim Lesen bildet dabei ein Forschungsfeld, in dem die Prozesse und Interaktionen dieser Subsysteme in einem klar definierten Rahmen untersucht werden können. Dabei geht es speziell um die Frage, wie viel Information visuell wahrgenommen wird, wie die kognitive Weiterverarbeitung der visuellen Buchstabeninformation über lexikalische Wortverarbeitung hin zu einem inhaltlichen Satzverständnis zeitlich koordiniert ist, und wie sich diese Prozesse auf das Verhalten – die Steuerung der Blickbewegung – auswirken.

Verschiedene Modelle zur Erklärung des spezifischen Blickbewegungsverhaltens beim Lesen wurden vorgeschlagen (für einen Überblick siehe Reichle, Rayner, & Pollatsek, 2003). Einige Modelle basieren auf der Annahme serieller Aufmerksamkeitsverschiebung von Wort zu Wort, wohingegen andere verteilte Aufmerksamkeit auf eine Region mehrerer Wörter im Satz gleichzeitig annehmen. Da Aufmerksamkeit eng mit der eigentlichen Wortverarbeitung assoziiert ist, besteht ein wesentlicher Unterschied zwischen den Modellen darin, dass die eigentlichen Wortverarbeitungsprozesse entweder ebenfalls strikt seriell oder parallel erfolgen.

Trotz solch entscheidender Unterschiede im zeitlichen Verlauf der Wortverarbeitung können beide Modellklassen viele der Benchmark-Effekte beim Lesen hinreichend erklären. Tatsächlich scheint es nicht viel empirische Evidenz zu geben, die die Grundannahmen der Modelle falsifizieren könnte. Die Frage, ob und wie noch nicht direkt angesehene Wörter rechts der Fixation die Blickbewegung beeinflussen, wird in der Debatte über serielle oder parallele Wortverarbeitung oft als entscheidend betrachtet. Insbesondere wird diskutiert, bis zu welcher Entfernung parafoveale Wörter vorverarbeitet werden und wie das die gegenwärtige und folgende Wortverarbeitung beeinflusst.

In einer Serie von vier Leseexperimenten wurde die Vorverarbeitung von Wörtern an den Grenzen der Wahrnehmungsspanne untersucht. Die vorliegende Arbeit versucht zudem, über einen einfachen Existenzbeweis der Vorverarbeitung von Wörtern in solchen Distanzen hinaus zu gehen. Mit einer Manipulation, die verschiedene Quellen solcher weitreichenden Vorverarbeitungseffekte dissoziiert, können Nutzen und Kosten der parafovealen Vorschau in einer einzigen Analyse untersucht und über eine Zielregion von drei Wörtern hinweg verfolgt werden. Dieselbe Manipulation überprüft gleichzeitig die Rolle okulomotorischer Fehler als Ursache für nicht lokale, verteilte Effekte beim Lesen. Die Ergebnisse tragen zu einem differenzierteren Verständnis der Wortverarbeitung in der Wahrnehmungsspanne und der zeitlich-räumlichen Verteilung der Aufmerksamkeit beim Lesen bei.

ABSTRACT

Cognitive psychology is traditionally interested in the interaction of perception, cognition, and behavioral control. Investigating eye movements in reading constitutes a field of research in which the processes and interactions of these subsystems can be studied in a well-defined environment. Thereby, the following questions are pursued: How much information is visually perceived during a fixation, how is processing achieved and temporally coordinated from visual letter encoding to final sentence comprehension, and how do such processes reflect on behavior such as the control of the eyes' movements during reading.

Various theoretical models have been proposed to account for the specific eye-movement behavior in reading (for a review see Reichle, Rayner, & Pollatsek, 2003). Some models are based on the idea of shifting attention serially from one word to the next within the sentence whereas others propose distributed attention allocating processing resources to more than one word at a time. As attention is assumed to drive word recognition processes one major difference between these models is that word processing must either occur in strict serial order, or that word processing is achieved in parallel.

In spite of this crucial difference in the time course of word processing, both model classes perform well on explaining many of the benchmark effects in reading. In fact, there seems to be not much empirical evidence that challenges the models to a point at which their basic assumptions could be falsified. One issue often perceived as being decisive in the debate on serial and parallel word processing is how not-yet-fixated words to the right of fixation affect eye movements. Specifically, evidence is discussed as to what spatial extent such parafoveal words are previewed and how this influences current and subsequent word processing.

Four experiments investigated parafoveal processing close to the spatial limits of the perceptual span. The present work aims to go beyond mere existence proofs of previewing words at such spatial distances. Introducing a manipulation that dissociates the sources of long-range preview effects, benefits and costs of parafoveal processing can be investigated in a single analysis and the differing impact is tracked across a three-word target region. In addition, the same manipulation evaluates the role of oculomotor error as the cause of non-local distributed effects. In this respect, the results contribute to a better understanding of the time course of word processing inside the perceptual span and attention allocation during reading.

CHAPTER 1

WORD PROCESSING IN THE PERCEPTUAL SPAN: THEORETICAL CONCEPTS AND EMPIRICAL EVIDENCE IN READING RESEARCH

CHAPTER 2

OPTIMIZING PARAFOVEAL PROCESSING IN THE N+2-BOUNDARY PARADIGM: EXPERIMENT 1

CHAPTER 1
WORD PROCESSING IN THE PERCEPTUAL SPAN: THEORETICAL CONCEPTS AND EMPIRICAL EVIDENCE IN READING RESEARCH

In contrast to verbal speech in which each element is articulated word-by-word and information serially accumulates over time, written language differs in that all words of a sentence, paragraph, or page are presented at once. This does not necessarily mean that all this information is perceived and processed simultaneously. In fact, limitations of the visual system and the perceptual span during reading force us to move the eyes across the page and to bring new regions of text into direct vision for more detailed inspection and processing. Moreover, reading does not only consist of encoding perceptual information but also of processes such as retrieving the associated meaning from the visual word percept and integrating it into the sentence context. Limitations are also assumed for such higher-level cognitive functions. One major goal of reading research is, therefore, to understand the interplay of both low- and high-level components in word recognition during reading and their impact on the when- and where-decisions of the corresponding movements of the eyes. The present chapter aims at embedding the questions investigated in Chapters 2, 3, and 4 into the underlying theoretical debates on attention allocation inside the perceptual span during reading. As these debates comprise again many other topics in reading research and directly connect with plenty other fields of cognitive science, the focus is set selectively on issues that will become relevant throughout the following chapters.

1.1 Basic theoretical concepts in reading research

In the following, eye movements will briefly be introduced as a behavioral measurement to examine online moment-to-moment processing during natural reading (for comprehensive reviews see Inhoff & Radach, 1998; Radach & Kennedy, 2004; Rayner, 1998, 2009). With respect to the physiology of the eyes, the visual system designates the outer limits for how much can be possibly viewed within a single gaze. The second subsection, therefore, contrasts the physiological evidence on vision with psychological research on the size of the perceptual span in reading. The results support the notion of effective use of information even beyond the word currently looked at and underscore the important role of attention in word recognition. In the final subsection, such evidence is discussed with respect to the major approaches of serial and parallel-distributed attention determining the time course of word processing in the perceptual span.

1.1.1 Eye-movements and processing measures

The behavior of the eyes during reading can be distinguished into two different events. Fast movements are called *saccades* and bring the eyes from one location to the next in a sentence.

Saccades can therefore guide the eyes towards new and informative regions in the text. Most saccades target at the next word in sequence, but if the next word is short and easy to process it can also be skipped and not be fixated at all. Other words are refixated and fixated twice or more before moving on to another word. Occasionally, the eyes go back in the sentence to a word that was already inspected or skipped before (i.e., inter-word regression). In summary, the trajectory of the eyes during reading seems more complex and dynamic than strict left-to-right movements.

Between saccades, there are periods of virtual inaction, so called *fixations*, in which the eyes rest on a word for about 200-250 ms. The time readers spend on a word is, for example, sensitive to the processing difficulty of the fixated word such as its printed word frequency (i.e., the number of occurrences of a given word in a representative selection of texts). Fixation durations, therefore, are taken as indicators for word processing and the time required accessing its representation in the mental lexicon (Just & Carpenter, 1980; Rayner & Duffy, 1986).

To analyze individual word-processing times, fixation durations are classified in order to constitute a meaningful behavioral measurement. The present work mainly focuses on first-pass measures which define the fixation durations on a word when it is first encountered during reading. Most frequently used are single fixation durations (SFDs), first fixation durations (FFDs), and gaze durations (GDs). SFDs reflect cases in which a word is fixated only once before moving to a next word. FFDs subsume all words' initial fixations only, irrespective of whether the word is refixated or not. Finally, GDs are computed as the sum of all first-pass fixations on a word including all refixations before leaving to another word. As a consequence, FFDs contain the full subset of SFDs while GDs contain the full subset of both first and single fixation cases.

1.1.2 The perceptual span in reading

Physiologically, visual acuity of the retinal image which is established during each fixation is rapidly decreasing from the location that is directly looked at. A narrow region around the fixation position (the central 2° of vision; e.g., Hirsch & Curcio, 1989) provides the highest image resolution and, therefore, allows the most detailed analysis of the visual input and the fastest processing. Beyond this region of foveal vision, visual acuity is declining in parafovea. Thus, the physiology of the visual system places first constraints on what can be perceived during a single fixation when reading text.

The region of effective vision from which useful information is acquired during reading is defined as the *perceptual span*. The size of the perceptual span has been studied in gaze-contingent display-change (GCDC) experiments using a moving window (McConkie & Rayner, 1975). Contingent on the current gaze position of the eyes on a computer monitor, only a pre-defined area of text is visible around the fixation location while the rest of the text is masked and, for example, replaced by different letters (see Figure 1.1). The size of the

Moving window paradigm

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xxxx xx x xxxxxxxx xxx xxxxxxxxxtion purposes.
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Figure 1.1 The moving-window paradigm. A pre-defined window of visible text is moving contingent on the current gaze position (asterics) across the sentence. Outside the window the text is masked, for example, with x-strings preserving word-length information.

window of visible text is now varied until reading speed (or other eye-movement indicators) is close to normal reading without a window. The minimal window size needed for normal reading provides an estimate of how much information is effectively used during reading.

For alphabetic languages such as English, the findings with the moving-window paradigm suggest that the perceptual span extends from 3-4 letters to the left up to 14-15 letters to the right of a given fixation (e.g., McConkie & Rayner, 1976; Rayner, Well, & Pollatsek, 1980). With an average size of 18 ± 1 letter spaces, the perceptual span comprises as much as one word to the left and up to two words to the right of a currently fixated word. Further studies showed, however, that the region in which words are identified to a degree at which spelling errors can be detected (i.e., false or transposed letters) is much smaller. The latter identification span does not exceed 7-8 letters to the right of fixation (Underwood & McConkie, 1985). In addition, it has been shown that the span size decreases with increasing foveal processing load (Henderson & Ferreira, 1990). If the currently fixated word in foveal vision is difficult to process, the uptake of parafoveal information to the right of fixation seems to be reduced.

With respect to parafoveal processing, these results are interesting for at least two reasons. First, the findings indicate that during reading information is used not only from the word currently fixated but also from not-yet-fixated words to the right of fixation. Second, as Figure 1.2 illustrates, the strong asymmetry of the perceptual span in reading stands in direct contrast to the physiological symmetry of acuity decrease on the retina relative to the fovea. The larger extent of the perceptual span into the direction of reading suggests that central cognitive factors such as attention play a significant role in modulating and/or limiting the visual input on each reading fixation.

1.1.3 Attention and word recognition

Attention is commonly assumed to drive word recognition in reading and is directly associated

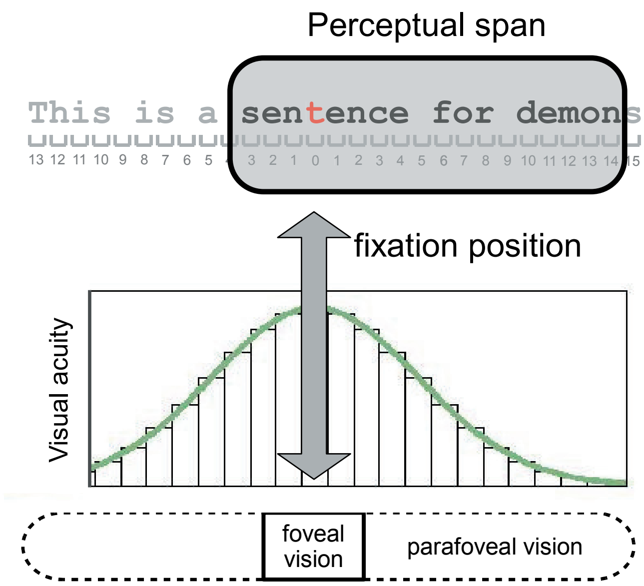

Figure 1.2 The perceptual span in reading. Illustrated is the contrast between the asymmetry in the size of the perceptual span (above) and the symmetry in the decreasing visual acuity around the fixation position (below).

with lexical processing. However, some levels of lexical access might as well be automatic such as the activation of phonological codes (Perfetti, Bell, & Delaney, 1988) which can automatically access the semantic meaning of the word (Lesch & Pollatsek, 1993). In fact, early works have proposed theories trying to explain reading by automatic information processing only (LaBerge & Samuels, 1974). Nevertheless, if attention lapses completely during reading as is the case when zoning out and thinking about something different, text comprehension suffers seriously (e.g., Schooler, Reichle, & Halpern, 2004).

Given that attention is mandatory for at least some stages of lexical processing and sentence comprehension, the findings from moving-window experiments suggest that all words inside the perceptual span receive some amount of attention during a given fixation. If not, reducing the window size should not have a detrimental effect on reading performance. However, it is not clear how precisely attention is allocated across the perceptual span. One influential approach assumes that word processing is based on *serial attention shifts* (SAS) and attention is restricted to only one word at a time (McConkie, 1979; Morrison, 1984; Rayner, Reichle, & Pollatsek, 1998). However, covert attention can be shifted to the next word without eye movements. If processing the foveal word is easy and fast and terminated before the saccade to the next word is executed, the neighboring word can be processed in parafoveal vision without being fixated. From this perspective, the perceptual span reflects the average area across which attention is sequentially

[1] The reason for introducing a new term is the attempt to compare the competing approaches on the same abstraction level. While SAS defines the time course of attention on a rather general level, an attention gradient provides additional information related to the processing efficiency at different eccentricities in the perceptual span. In fact, implementation of SAS in E-Z Reader also considers decreasing processing efficiency with increasing distance in parafoveal vision. However, the latter is a fully implemented computational model which is difficult to compare with a purely theoretical concept or model of the time course of attention allocation during reading (see discussion in 5.3).

shifted during a single fixation prior to saccade execution, and the accumulation of subsequent word information does not start before all prior words are lexically accessed.

A competing approach is based on *parallel distributed attention* (PDA) also known as attention gradient or processing gradient assumption[1]. In this framework, attention is not restricted to a single word unit but is allocated across several words simultaneously. As a result, accumulation of word information for all words inside the perceptual span can start at the same time soon after the beginning of fixation. In summary, both approaches account for parafoveal processing during reading, but on the grounds of different time-course assumptions of word processing inside the perceptual span. In the SAS-framework, processing is achieved in a strictly serial fashion with parafoveal word information being available only after foveal processing is terminated. In contrast, the PDA-framework permits parallel word processing and parafoveal information is (at least partly) available during foveal word processing.

1.2 Parafoveal processing in the perceptual span

The size of the perceptual span suggests that parafoveal word information is used at least from one or two words to the right of fixation. Given that a word n is fixated, characteristics of the subsequent words n+1 and n+2 may be acquired parafoveally and have a measurable impact on reading. In the following section, the empirical evidence for parafoveal preview in the perceptual span is reviewed. This review is not intended to be exhaustive. For example, it mainly focuses on studies that used the boundary paradigm in sentence reading tasks. While the boundary paradigm has also been criticized (O'Regan, 1990), it constitutes the major experimental research on parafoveal processing in reading. However, some important work has been done implementing a similar boundary technique but reading single word lists. Isolated word paradigms differ in that participants cannot be asked to read for comprehension but are instructed, for example, to search the word list for a member of a given word category. Other studies investigated parafoveal processing by asking participants to name a target word in foveal vision which was previously primed in parafoveal vision. The differences between studies may constrain the direct relevance of the results for parafoveal processing in normal reading. However, similarities in the results between paradigms might also reflect principles that can be generalized across tasks.

1.2.1 The boundary paradigm

How parafoveal processing of the word(s) to the right of fixation affects eye-movement behavior in reading has been extensively studied in the boundary paradigm (Rayner, 1975). In contrast to the moving-window paradigm, the boundary paradigm is based on GCDCs of only one single target word (see Figure 1.3, upper panel). Reading a sentence on a computer monitor, an invisible

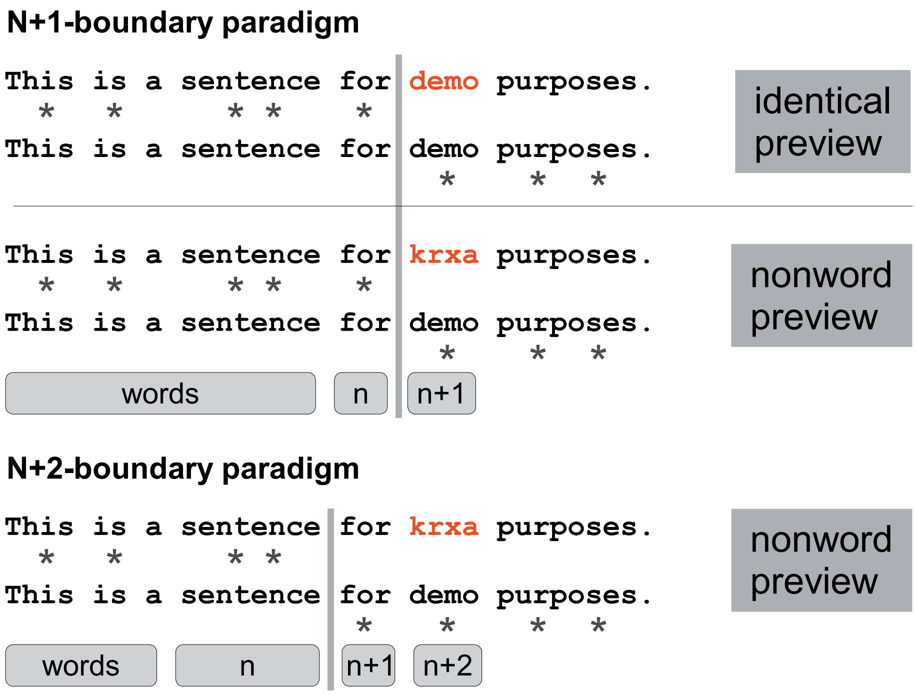

Figure 1.3 The boundary paradigm. In the upper two panels, preview of word *n*+1 is manipulated. Word *n*+1 (red) is either presented as an identical (upper panel) or nonword preview (middle panel). If the eyes (asterics) cross the boundary after word *n*, the preview is replaced with the correct target word (black). In the lower panel, the same principle is illustrated for previewing word *n*+2, the word two words to the right of the invisible boundary. The condition with identical preview of word *n*+2 is, however, omitted.

boundary is located at the last letter of a given word *n*. During fixations prior to this boundary, preview of the parafoveal word *n*+1 is manipulated, for example, by presenting a nonword random-letter string. As soon as the eyes cross the boundary the *n*+1 preview is replaced by another word such that during its fixation only the correct target word is available for processing. Trials with incorrect word *n*+1 preview can then be compared to trials in which identical preview of word *n*+1 was provided throughout sentence reading. The boundary technique, therefore, permits experimental control over parafoveal information extraction: Controlling the information overlap between preview and target word allows investigation of what type of information is effectively preprocessed in parafoveal vision.

Two effects of parafoveal processing are commonly examined in the boundary paradigm. Differences in fixation durations on the target word *n*+1 give rise to whether previewing this word in parafoveal vision had a facilitating effect on its later word recognition. Shorter fixation durations on the target word if preview was available relative to longer fixation durations if preview was denied indicate a *preview benefit* (PB; see Rayner, 1998, 2009, for a review). By definition, the PB effect is measured on the target word when it is finally fixated, that is after the eyes crossed the boundary and the display change of the preview has been executed. From this perspective, the PB effect is a rather late and indirect measurement of parafoveal processing. A direct effect should be expected on the pre-boundary word *n* at the moment when word *n*+1 is essentially processed in parafoveal vision. Any such influence of parafoveal word properties on foveal word *n* processing are referred to as *parafoveal-on-foveal* (PoF) effects (see Kennedy, 1998).

1.2.2 Preview effects in reading

Parafoveal processing of the neighboring word *n*+1 is well established. Persuasive evidence has accumulated that sublexical word properties such as orthographic letter information can be gained from parafoveal vision. In addition, also higher-level lexical information such as the word's frequency or predictability seem to modulate parafoveal processing. To this point evidence from the boundary paradigm suggests that the type of information extracted from a parafoveal preview exerts different effects on ongoing word recognition processes. Therefore, results are reviewed seperately with respect to PB and PoF effects.

Preview benefit effects of word *n*+1

Research with the boundary paradigm established substantial PB on the target word *n*+1: Fixation times on word *n*+1 are about 20-50 ms shorter if identical preview of the target word was available throughout sentence reading compared to when its preview was denied (for a review see Rayner, White, Kambe, Miller, & Liversedge, 2003). The question of what type of information can be extracted from word *n*+1 has motivated many studies in which the information overlap between preview and target word was varied. Comparing the PB effect for nonword previews which were visually similar or dissimilar to the target suggested that low-level visual information of the parafoveal word shape can be used to facilitate processing when the word is then fixated (Balota, Pollatsek, & Rayner, 1985; Drieghe, Rayner, & Pollatsek, 2005). If the visual preview information was dissimilar to the target, processing times on the target word were significantly longer.

Rayner, McConkie, and Zola (1980) in a naming task presented single words parafoveally which were written in alternating upper- and lower-case letters (e.g., cHeSt) and were then changed into the inverse alternation sequence (e.g., ChEsT) when they appeared in foveal vision. Although the visual information changed for each letter of the target word, the results showed substantial PB in naming the target word in foveal vision. Therefore, the overlap in visual information between preview and target word cannot be the only source of PB. In fact, it has been argued that integrating information of successive fixations is achieved on the level of abstract letter codes (McConkie & Zola, 1979; Rayner et al., 1980).

Other sources of PB seem to be shared phonological codes between preview and target (Chace, Rayner, & Well, 2005; Henderson, Dixon, Petersen, Twilley, & Ferreira, 1995; Miellet & Sparrow, 2004; Pollatsek, Lesch, Morris, & Rayner, 1992) and the orthographic overlap of partial letter information that can be integrated across saccades (Inhoff, 1989, 1990; Inhoff, Radach, Eiter, & Juhasz, 2003; Inhoff & Tousman, 1990; Rayner, Well, Pollatsek, & Bertera, 1982). In fact, presenting the first three letters of a word in parafoveal vision is almost as beneficial as presenting the whole word (Rayner et al., 1982).

In addition to such lower-level sublexical influences of parafoveal previews, PB is also greater if the upcoming word *n*+1 is highly predictable from the sentence context (Balota et al., 1985) or highly frequent in language use (Henderson & Ferreira, 1990; Inhoff et al., 2003; Inhoff & Rayner, 1986; Kennison & Clifton, 1995), both higher-level linguistic variables that are associated with processing ease. However, it must be noted that the latter studies do not investigate how linguistic information is integrated across saccades. In contrast, they document that more preview information is gained from an easy high predictable preview than from a difficult low predictable word. This suggests that preview information is more effectively combined with and integrated into word recognition processes of a word that is easy rather than difficult. It does not test whether the information that was integrated into target word processing was of higher-level lexical nature.

Inter-saccadic integration of lexical word information has so far only been investigated manipulating the semantic relatedness between preview and target word (but see Chapter 4, Experiment 3). If target word reading times were shorter in case of semantically related preview, this would indicate that semantic codes derived from the parafoveal preview could be succesfully transferred into foveal target-word processing. Whereas most of the evidence has argued against such semantic PB in alphabetic languages (Altarriba, Kambe, Pollatsek, & Rayner, 2001; Inhoff, 1982; Inhoff & Rayner, 1980; Inhoff, Starr, & Shindler, 2000; Hyönä & Häikiö, 2005; Rayner, Balota, & Pollatsek, 1986; Rayner & Morris, 1992), recent research suggested that semantic information might be parafoveally extracted only in a certain, probably relatively early, time window (Hohenstein, Laubrock, & Kliegl, 2010).

Parafoveal-on-foveal effects of word *n*+1

In contrast to the well established PB effect on word *n*+1, evidence for direct PoF effects on the pre-boundary word *n* is much more controversial. The effects seem to vary with respect to the parafoveal word properties being investigated and the paradigm used. Moreover, the direction of PoF effects also varies between studies. In some experiments, a positive PoF effect is obtained with longer foveal fixation durations if the parafoveal word is difficult (e.g., Inhoff, Radach, Starr, & Greenberg, 2000) whereas other results rather suggest a magnetic effect of attraction with parafoveal difficulties initiating an early saccade towards the parafoveal target (e.g., Hyöna & Bertram, 2004). The latter case corresponds to a negative PoF effect.

Several studies agree on finding that visually distinct random-letter previews of word *n*+1 (nonwords) prolong fixation durations on the prior word *n* (Drieghe, Rayner, & Pollatsek, 2008; Inhoff, Radach et al., 2000; Inhoff, Starr et al., 2000). Such orthographic irregularity effects seem to generalize to tasks in which words are read in isolation and participants search a list of nouns for a member of a semantic category (e.g., clothes; Kennedy, 2000; Vitu, Brysbaert, & Lancelin, 2004). Manipulating the orthographic familiarity of only the word's beginning letters affirmed such positive PoF effects in pre-boundary fixation durations (Pynte, Kennedy, & Ducrot, 2004; White, 2008; but see White & Liversedge, 2004). The results suggest that sublexical properties of the neighboring word *n*+1 are not only integrated into later word recognition processes but also directly modulate the time spent on the foveal word.

For higher-level lexical information, the evidence is less clear. Confirmation for PoF effects in response to the frequency of word *n*+1 mainly comes from isolated-word studies (Kennedy, 1998; Kennedy, Pynte, & Ducrot, 2002). In contrast to the studies reported above, the PoF effects were negative showing shorter not longer pre-boundary fixation durations in the presence of parafoveal processing difficulties (e.g., long and low-frequent words *n*+1). The task used in those studies was, however, criticized to impose different processing or attentional strategies than sentence reading (see Reichle et al., 2003). Frequency effects from uninspected words in parafoveal vision could also be demonstrated in a classic boundary paradigm manipulating the preview of a target word embedded in a sentence context (Hyönä & Bertram, 2004). However, the results did not replicate systematically across experiments, especially if frequency was crossed with other variables such as the word length of the parafoveal word (Hyönä & Bertram, 2004; Pynte et al., 2004; Rayner, Warren, Juhasz, & Liversedge, 2004; White, 2008).

Clear support for direct preprocessing effects comes from regression analyses of large corpora of texts. Variables such as the frequency and predictability of the upcoming word *n*+1 consistently affected current word *n* fixations (e.g., Kennedy & Pynte, 2005; Kliegl, Nuthmann, & Engbert, 2006; Pynte & Kennedy, 2006, 2007). In fact, corpus analyses reliably show distributed processing effects with a given fixation reflecting processing not only of the currently fixated word *n* but also of the word to the left (i.e., word *n*-1) and to the right (i.e., word *n*+1). Effects of the upcoming word *n*+1 to the right of fixation indicate PoF effects. However, corpus analyses have been criticized for problems associated with the correlational nature of regression analyses, and for a lack of experimental control over a broad range of word properties (Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007). In response, Kliegl (2007) documented the stability of results from corpus analyses across nine different groups of participants in an advanced regression analysis including several additional covariates. Moreover, replicating distributed effect patterns in a corpus analysis reading randomly shuffled text (Schad, Nuthmann, & Engbert, 2010) further supports the validity of corpus-analytic evidence in a perfectly randomized experiment. Nevertheless, the consistent findings of PoF effects in corpus analyses seem to contradict with the more controversial picture when the boundary paradigm is used.

Parafoveal preview of word *n*+2

The picture becomes even more heterogeneous if parafoveal processing of word *n*+2 is considered. Investigating the spatial limits of parafoveal processing in the boundary paradigm seems to be the logical consequence of the results on the size of the perceptual span during reading (see 1.1.2). Rayner, Juhasz, and Brown (2007) first introduced a boundary experiment in which they investigated whether *n*+1 preview effects generalize to word *n*+2. In contrast to earlier studies, the location of the invisible boundary was varied. The boundary was either located prior to the target word (see Figure 1.2, upper two panel) or before the word preceding the target word (see Figure 1.2, lower panel). The first case characterizes the classical situation in which preview of word *n*+1 is controlled. In the latter case, relative to the pre-boundary word *n*, there is an additional post-boundary word *n*+1 preceding the target word *n*+2, in the following referred to as the *n*+2-boundary paradigm.

The target word (i.e., word *n*+1 or *n*+2) was either previewed as the identical word, an alternative word, or as a nonword preview during pre-boundary fixations. In line with previous research, reliable preview effects were observed when the target word was word *n*+1. There were no effects if the boundary was moved forward about one word and the target word was word *n*+2. To increase the chance that word *n*+2 falls into the perceptual span, Rayner et al. (2007) used short three- to four-letter words *n*+1 and *n*+2 in a second experiment. However, even under this optimized conditions they did not find any evidence for parafoveal processing of the target word *n*+2, neither a PB effect on word *n*+2 nor PoF effects in the pre-target region.

In contrast to the absence of preview effects in the *n*+2-boundary paradigm, such effects were observed in a corpus analysis (Risse, Engbert, & Kliegl, 2008). It has to be noted that preview of word *n*+2 is not experimentally controlled in corpus analyses. Therefore, the only preview effect that can be directly compared to results in the boundary paradigm is the PoF effect prior to any display changes. Risse et al. (2008) found a significant interaction of the frequency and length of word *n*+2 in fixation durations on word *n*. SFD on word *n* were longer if word *n*+2 was low rather than high frequent. This effect was, however, constrained to short words *n*+2 (about 7 letters or less) and to short two- or three-letter words *n*+1 preceding word *n*+2. If word *n*+1 was four or five letters long, the *n*+2 PoF effect was not significant. As first evidence, *n*+2 preview effects seem to be small (i.e., about 15 ms) and highly sensitive to the word length of the intermediate word *n*+1.

1.2.3 Parafoveal cross-talk and oculomotor error

Besides being an interesting empirical phenomenon, parafoveal processing has received attention because it is assumed to uncover the explanatory limits of current reading models of eye-movement control. It has been argued that PDA models predict a greater spatial extent of parafoveal processing than SAS models. For example, if word *n*+2 falls inside the perceptual span, preview effects should not be restricted to word *n*+1 if attention is distributed across all words inside the perceptual span in parallel. Shifting covert attention serially up to two words ahead of the eyes is rather an exception, not the rule (Rayner et al., 2007). Therefore, in SAS models, preview effects of word *n*+2 should be less likely than effects of the neighboring word *n*+1.

In addition, the models differ in the type of preview effects they predict. As described above (see 1.1.3), both concepts of attention and word processing allow for parafoveal processing of not-yet-fixated words to the right of fixation. Thus, both approaches predict later PB effects on the target word if it was previewed in parafoveal vision. In contrast, direct PoF effects while the preview is still in parafoveal vision have been discussed as evidence for cross-talk between processing several words in parallel (e.g., Kennedy, 1998). If attention is shifted from word to word and word identification is serial, processing the upcoming word cannot directly affect processing of the previous word anymore. The absence of PoF effects in some studies is, therefore, viewed as evidence for the basic assumption of serial word processing (e.g., Rayner et al., 2007).

At the same time, the inconsistency in results has motivated skepticisms about PoF effects being genuine due to parallel word processing. It has been argued that, if PoF effects are observed, they may reflect oculomotor artefacts and not parallel processing cross-talk. Due to oculomotor error inherent in any saccadic movement (McConkie, Kerr, Reddix, & Zola, 1988), some fixations might not be located on the intended word but are mislocated. In reading, this may result in the following situation: A saccade targeted to word *n*+1 may fall short and lead to an unintended re-fixation of word *n*. If such a mislocated fixation is not immediately corrected, it may reflect processing of the attended word *n*+1 rather than the currently fixated word *n* (Rayner et al., 2004). Thus, fixation durations on word *n* should depend on the processing demand of the neighboring word *n*+1 – nominally a PoF effect, but in agreement with SAS models without relaxing the assumption on strictly serial word-recognition processes.

Drieghe, Rayner, and Pollatsek (2008) investigated mislocated fixations as a possible explanation for PoF effects in the boundary paradigm. They found that PoF effects were restricted to word *n* fixations close to the boundary only. Moreover, such near-boundary fixations were independent of the frequency of the currently fixated word *n*. They argued that such an effect pattern is compatible with oculomotor error in SAS models. If word *n*+1 is attended and processed, mislocated fixations on word *n* should be determined by the processing difficulty of word *n*+1, not of word *n*. In addition, finding such effects only for word *n* fixations close to the boundary was taken as further support for oculomotor error which should be more likely at the word boundaries (Nuthmann, Engbert, & Kliegl, 2005).

The mislocated-fixation interpretation was challenged with a corpus analysis (Kennedy, 2008) showing that the orthographic familiarity of an upcoming word n+1 had an effect for fixation locations up to seven characters prior to word n+1. Such long-range PoF effects seem to be rather genuine unlikely to be attributed to oculomotor artefacts. Obviously, the major difficulty in investigating whether PoF effects are genuine or due to mislocated fixations is that it cannot be easily distinguished whether a given fixation is intended or the result of oculomotor error. Finding PoF effects for a broad range of eccentricities from the parafoveal target falsifies the *mislocated-fixation hypothesis* only if oculomotor error is assumed to be smaller than this range. Conversely, even if PoF effects were constrained to near-boundary fixations only, this does not rule out its interpretation in terms of cross-talk: Visual acuity and with it the processing efficiency decreases with increasing eccentricity from a given fixation position and, consequently, cross-talk is expected to be smaller for fixations further away from a parafoveal target.

Given that mislocated fixations often provide a feasible alternative for effects of distributed processing, it seems an important goal to find paradigms that can distinguish between genuine effects from cross-talk and preview effects from an unintended fixation position. While some studies considered conditions in which critical effects should not occur even under the assumption of oculomotor error (Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Angele & Rayner, in press; Wang, Inhoff, & Radach, 2009), these studies require arguing the null-hypothesis to favor SAS over PDA models. Thus, at present, a convincing manipulation to dissociate between the two hypotheses is still missing.

1.3 Overview of the present experiments

A series of four experiments focuses on parafoveal processing at the spatial limits of the perceptual span. All experiments aim at contributing to the understanding of whether word n+2 is previewed during normal reading and how such information is integrated into word recognition processes across a three-word target region. However, the experiments also cover issues in which they differ from each other.

Chapter 2 introduces an n+2-boundary study similar to the one reported by Rayner et al. (2007). The primary goal of Experiment 1 was to optimize the conditions under which preview effects of word n+2 may occur. Besides increasing the statistical power, word length of the pre-boundary word n was increased to minimize its skipping probability and, therefore, to maximize the probability of preprocessing the target word as a real n+2 preview during pre-boundary fixations. In addition, the intermediate word n+1 was constrained to three letters length and varied in its processing difficulty. Applying the same procedure for data selection and analysis as in the remaining experiments, Chapter 2 contains re-analyzed data published in Kliegl, Risse, and Laubrock (2007). It should be noted that the re-analysis partly deviated from the results previously reported. Differences will be explicated in more detail in the discussion of Experiment 1. Notwithstanding, the results suggest that under certain conditions preview effects can be obtained even up to word *n*+2. The findings further reveal that preview effects of word *n*+2 are non-local. They seem to leave traces directly on the pre-boundary word *n*, but mainly on the short post-boundary word *n*+1 or on the target word *n*+2, depending on which one was fixated first.

Chapter 3 investigates parafoveal processing of word *n*+2 from an individual-difference perspective and has been published in Risse and Kliegl (2011). Following up on research suggesting an age-related reduction in the rightward extent of the perceptual span during reading (Rayner, Castelhano, & Yang, 2009), Experiment 2 compared older and young adults in the same *n*+2-boundary paradigm introduced in Chapter 1. In contrast to the expectations, *n*+2 preview effects were obtained both for young and for older adults. In agreement with Experiment 1, *n*+2 effects were found on the short post-boundary word *n*+1 and on the target word *n*+2, but there was no evidence for *n*+2 PoF effects. Age groups did not differ in the size of the PB effect on the target word *n*+2 but they did differ in the *n*+2-effect on the pretarget word *n*+1. Moreover, older adults showed an attenuated *n*+1 PoF effect on word *n*. Young adults seemed to modulate their fixation durations more strongly in response to parafoveal processing difficulties particularly showing shorter fixations than older adults in the presence of low processing demand. The results are discussed in terms of age-related decline in resilience towards distributed processing while simultaneously preserving the ability to utilize parafoveal information up to word *n*+2.

The dissociation of age-associated decline in modulation ability on the one hand and preservation of parafoveal processing on the other hand provided first evidence for a qualitative difference between PB and PoF effect. Pointing towards a possible dissociation of different preview sources, this approach was elaborated and utilized in Chapter 4 to investigate the mislocated-fixation hypothesis. If one creates an experimental situation in which the intended saccade target is replaced prior to a mislocated fixation, the associated fixation duration should reflect processing the attended target and hence the difficulty after its replacement. If useful preview was available, there should even be a PB effect in mislocated fixations. In contrast, given a genuine PoF effect due to parallel processing the mislocated fixation should still show influences of the target word difficulty prior to its replacement. Therefore, Experiment 3 and 4 orthogonally manipulated the pre- and post-boundary difficulty of word *n*+2 in the standard *n*+2-boundary paradigm. When the eyes crossed the invisible boundary set after word *n*, an either easy or difficult word *n*+2 preview was replaced by an easy or difficult *n*+2 target. Given that short and easy words are often skipped and oculomotor error increases with increasing saccade amplitude, mislocated fixations were particularly expected to occur on the short post-boundary word *n*+1. The results of both experiments confirmed that fixation durations on word *n*+1 depended on the *n*+2 pre-boundary difficulty only and did not show effects of post-boundary processing of word *n*+2. Therefore, we obtained persuasive evidence for a delayed PoF effect on the post-boundary word *n*+1 which cannot be interpreted as a PB in mislocated fixations. The results suggest that immediacy of processing of word *n*+2 after the boundary manifests not before word *n*+2 is fixated. In addition, three influences of processing could be distinguished in a single target-word fixation: Besides an immediacy effect of the *n*+2 processing difficulty (i.e., *n*+2 post-boundary difficulty), there was a PB in case of correct preview (i.e., interaction of *n*+2 pre- and post-boundary difficulty) and additional costs of a difficult *n*+2 preview (i.e., *n*+2 pre-boundary difficulty) if word *n*+1 was successfully skipped. Taken together, the results question oculomotor error as an explanation for distributed processing effects.

The results of each experiment will be discussed in the respective chapters. Therefore, the last Chapter 5 summarizes some more general considerations about the debate on the time course of processing inside the perceptual span. The main focus will be on discussing possible implications of the present results for computational models of eye-movement control in reading. Moreover, the importance is emphasized to clearly dissociate the level of theoretical or conceptual models from the level of computational models. This is particularly important when formulating hypotheses that are supposed to test conclusively whether word processing is serial or parallel.

CHAPTER 2
OPTIMIZING PARAFOVEAL PROCESSING IN THE N+2-BOUNDARY PARADIGM: EXPERIMENT 1

Given the theoretical relevance of preview effects from word *n*+2, in particular for the debate on serial and parallel word processing (Kliegl, 2007; Reichle, Liversedge, Pollatsek, & Rayner, 2009), the first experiment was conducted as a variant of the *n*+2-boundary paradigm implemented in Rayner et al.'s study (2007). Several modifications were carried out with the goal to optimize the conditions of processing word *n*+2 in parafoveal vision.

2.1 Differences to previous studies

In contrast to Rayner et al. who varied the boundary location to investigate both preview of word *n*+1 and *n*+2, the present experiment aimed only at previewing word *n*+2. The boundary was thus fixed and always located at the end of word *n* followed by a three-letter word *n*+1. The subsequent word *n*+2 was either presented as the identical or as a nonword preview prior to crossing the boundary. Implementing only two instead of three *n*+2 preview conditions across 160 experimental sentences, we increased the statistical power for all analyses.

In addition, Rayner et al. used short words *n*+1 and *n*+2 to increase the likelihood that word *n*+2 fell into the perceptual span. Moreover, the pre-boundary word *n* was also very short and in almost all cases an article. As articles are skipped very often (Gautier, O'Regan, & Le Gargasson, 2000), in some proportion of cases participants might have previewed word *n*+2 from an *n*+3-distance. Minimizing the skipping probability of word *n*, we used rather long pre-boundary words in order to increase the chance for *n*+2 preview uptake.

Finally, we manipulated the lexical status of the three-letter word *n*+1 and with it its processing difficulty. In half of the sentences, word *n*+1 was an easy function word whereas in the other half it was a more difficult content word. The importance of this manipulation is twofold. First, attention is assumed to drive word recognition processes (see 1.1.3). Manipulating the attentional demand in parafoveal vision when increasing the processing difficulty of word *n*+1 should have an impact on processing word *n*+2 (cf., Yan, Kliegl, Shu, Pan, & Zhou, 2011). In fact, an easy word *n*+1 should increase the likelihood and the amount of processing word *n*+2 in parafoveal vision. Second, the manipulation of the lexical status of word *n*+1 allowed us to investigate preview effects of parafoveal processing of both words *n*+1 and *n*+2 with a single display change. Since preview of word *n*+1 is not varied across subsequent fixations, identical preview of word *n*+1 is gained on every fixation. Therefore, we can examine effects of the parafoveal processing difficulty of word *n*+1 only as an *n*+1 PoF effect on the pre-boundary word *n*.

Given these modifications, the following preview effects can be investigated in the *n*+2-

boundary paradigm: If word *n*+2 information is effectively used, there should be PB on the target word *n*+2. Moreover, the *n*+2 PB effect should be greater if word *n*+1 is an easy function word and does not need much attentional processing resources. In addition, there should be a direct effect of word *n*+2 in fixations on the pre-boundary word *n*. Such *n*+2 PoF effects should also be modulated by the processing difficulty of the intermediate word *n*+1. Likewise, differences in the *n*+1 processing difficulty might exert additional *n*+1 PoF effects in word *n* fixation durations. How the results coincide with predictions from SAS and PDA approaches will be outlined in the discussion at the end of this chapter.

2.2 Method

2.2.1 Participants

Data was collected from 30 students of the University of Potsdam who were all native German speakers. Participants had uncorrected or corrected-to-normal vision. For their one-hour participation they were paid 6 € or received course credit.

2.2.2 Sentence material

A three-word target region (i.e., word *n*, word *n*+1, and word *n*+2) was embedded in simple-structured main clauses without intra-sentential punctuation. Word *n* ranged from 4 to 13 letters in length (M = 7) averaging in word frequency to 295 per million. In half of the sentences, the neighboring word *n*+1 was a function word (i.e., preposition or conjunction) and in the other half, it was a content word (i.e., noun). In either case, word length was restricted to three letters. Mean frequency of function words averaged to 5,141 per million whereas content words were less frequent with 32 per million. Length of word *n*+2 ranged from four to seven letters (M = 5), with an average frequency of 769 per million. Target words were adverbs, adjectives, or verbs. Word-frequency norms were based on the *Digitales Wörterbuch der Deutschen Sprache des 20. Jahrhunderts* corpus (Geyken, 2007; Heister et al., 2011) incorporating 125 million words.

Sentences were constructed around the target region such that word *n* was never the first or second word, and word *n*+2 was never the last or next to last word in the sentence. The target region was equally distributed across five possible positions within sentences, with the words of interest constituting words 3-5, 4-6, 5-7, 6-8, or 7-9 in each sentence. Sentences contained 8 to 11 words in total (M = 9.7).

2.2.3 Apparatus and procedure

Participants were seated 60 cm in front of an Iiyama Vision Master Pro 514 monitor (resolution: 1024 x 768 pixel; 21 inch; refresh rate: 150 Hz). Their heads were positioned in a chin rest to

Function word n+1:

- *identical n+2 preview condition*

    Morgen soll es sonnig und leicht bewölkt sein.

    Morgen soll es sonnig und leicht bewölkt sein.

- *nonword n+2 preview condition*

    Morgen soll es sonnig und tarsbl bewölkt sein.

    Morgen soll es sonnig und leicht bewölkt sein.

    [transl.: Tomorrow it shall be sunny and slightly clouded.]

Content word n+1:

- *identical n+2 preview condition*

    Sie war in leuchtendem Rot weit zu erkennen.

    Sie war in leuchtendem Rot weit zu erkennen.

- *nonword n+2 preview condition*

    Sie war in leuchtendem Rot mcrf zu erkennen.

    Sie war in leuchtendem Rot weit zu erkennen.

    [transl.: She was in lucid red far to be recognized.]

Figure 2.1 Experimental conditions in Experiment 1. Two example sentences isslustrate the two lexical-status conditions of word n+1 (upper panel: function word; lower panel: content word). Each snetenc is shown in either the identical or nonword preview condition of word n+2. The target region is underlined, the invisible boundray is represented as a dotted line. An English translation is given below each block of example sentences.

minimize head movements. Reading was binocular and both eyes were monitored with an Eye-Link II system (SR Research, Osgoode, Ontario, Canada). Eye movements were recorded with a 500 Hz sampling rate and an instrument spatial resolution of 0.01º. Sentences were presented using regular Courier New 12 as font resulting in 2.2 characters per degree of visual angle.

Participants were calibrated binocularly using a standard 9-point grid and were recalibrated every 15 sentences. Additional calibrations became necessary if detection of the eyes at the initial fixation point failed two times in succession within a time window of 2 seconds prior to each sentence presentation. Participants read 6 practice and 160 test sentences for comprehension and were naive concerning the experimental manipulation. Single sentences were displayed horizontally on the center line of the monitor screen with a fixed sentence offset from the left monitor border. Before sentence presentation an initial fixation point was displayed. Designating the word center of the initial word in each sentence, its vertical position varied conditional on the first word's length. Valid detection of the gaze on the fixation point triggered sentence presentation which participants then terminated by fixating a point in the lower right corner. Sentence comprehension was tested on average every third trial by displaying a three-alternative multiple-choice question after completion of sentence reading.

A GCDC technique was implemented for the 160 test sentences (see Figure 2.1 for two different example sentences). An invisible boundary was placed at the right end of the last letter of a pre-specified word *n* followed by a three-letter post-boundary word *n*+1. During pre-boundary fixations, the target word *n*+2 was either presented as the true word (i.e., identical preview) or as a random string of letters (i.e., nonword preview). Nonword previews were generated online. Each letter of the target word *n*+2 was replaced with a different letter randomly chosen from a set of similar letters matched according to visual similarity in their spatial alignment. As soon as one of the eyes exceeded the boundary location, word *n*+2 was replaced with the correct target word, being replaced with itself in the identical preview condition. Experimental conditions were counterbalanced across participants. At the end of the experiment, participants were asked whether they noticed any display changes during reading the sentences.

2.2.4 Data selection

No participant reported to have noticed any display changes, therefore data of all 30 subjects were analyzed. 532 out of a total of 4,800 sentences were lost due to blinks and signal losses of the eye-tracking system removing 11 % of the data. Saccades were detected offline using the velocity-based detection algorithm by Engbert and Mergenthaler (2006; Engbert & Kliegl, 2003). While reading was binocular right-eye data were analyzed only. Data were selected on two levels according to criteria for sentences and individual fixations.

On sentence level, all sentences were removed in which an invalid display change was detected. Due to system delays within the eyetracker (SR Research Ltd., 2006) and the refresh rate of the monitor not all display changes necessarily had been completed before the eyes landed on a word after the boundary. To select only those trials in which the display change terminated within the saccade that crossed the boundary we post hoc determined the time of the termination of each trials visual display change on the monitor. Therefore, we estimated the time left of the monitor's refresh cycle at the moment of the first eye crossing the boundary and added this to the time of the internal display-change trigger (see Appendix A for further details). The total delay of the display change relative to its trigger averaged to 8.3 ms, ranging from 5 to 11.7 ms. For all analyses, we only considered trials in which the display change on the monitor occurred between the onset and offset of the forward, binocular saccade exceeding the boundary. As such, additional 17 % of the sentences were excluded leaving 3,460 sentences for further analyses.

On the fixation level of each valid sentence, within-letter refixations (reading microsaccades) were identified and the preceding and following fixation duration were combined. Moreover, invalid fixations within the target region were defined as (i) being shorter than 50 ms or longer than 750 ms, (ii) being the first or last fixation in the sentence, or (iii) when the left eye fixated a different word than the right eye. This last criterion was added in order to exclude cases in which the left eye was ahead of the right eye and may have fixated the parafoveal preview prior to crossing the boundary. The dependent measures were generated before excluding invalid fixations. For cumulative fixation duration measures such as GDs the data point was excluded if one of its constituent fixations was invalid. Thus, a total of 37 % of the recorded word-based fixations in the target region were excluded (26 % for word *n*, 53 % for word *n*+1, 38 % for word *n*+2). This still left 3,029 valid GDs on word *n*, 1,249 on word *n*+1, and 2,428 on word *n*+2.

2.2.5 Data analysis

Separate linear mixed models (LMMs; Baayen, Davidson, & Bates, 2008) were fitted for each of the three words in the target region using the lmer program (lme4 package; Bates & Meachler, 2010) in the R system for statistical computing (R version 2.11.1, The R Foundation of Statistical Computing, 2010). Using LMMs is advantageous over the traditional analysis of variance (ANOVA) approach in that it allows simultaneously specifying both the subject and item variance as crossed random effects. Thus, differences in the effect pattern between F1 (over participants) and F2 (over items) statistics that often complicate the interpretation of ANOVA results are avoided by considering both sources of variance in one single analysis. The LMM approach has further proven to be a powerful tool in analyzing data sets with unbalanced designs and is used in various other scientific fields such as linguistic (Baayen, 2008) and ecology (Bolker et al., 2008).

As fixed effects, we specified the experimental variables such as preview of word *n*+2 (identical vs. nonword preview) and the lexical status of word *n*+1 (function vs. content word). Since the short post-boundary word *n*+1 was frequently skipped, we further included skipping of word *n*+1 (fixated vs. skipped) as a post-hoc factor for predicting fixation durations on the pre-boundary word *n* and the target word *n*+2. Model comparisons that are not reported here confirmed this decision resulting in a significantly improved model fit if skipping of word *n*+1 was included. For the analyses of fixation durations on the post-boundary word *n*+1 if it was fixated and not skipped, we ran reduced LMMs without considering skipping of word *n*+1. All fixed effects were effect coded using contrast coefficients of -0.5 and 0.5. Therefore, the LMMs return the grand mean dependent variable as intercept and the fixed-effect parameters as deviations from the grand mean. In this sense, fixed effects can be interpreted according to main effects and interactions in an ANOVA.

Participants, the unique word index, and sentence number (i.e., items) were submitted as random effects. For each analysis the regression coefficients (*b*), the standard errors (*SE*s) and *t* values for an upper-bound of n degrees of freedom computed as n observations minus n fixed effects are reported. A fixed effect is considered significant with absolute *t* values > 2.00 reflecting at least two SEs. Analyses of the LMM residuals suggested that log-transformed fixation durations

Lexical status of word *n*+1	Preview of word *n*+2	FFD		GD	
		Skipping word *n*+1		Skipping word *n*+1	
		fixated	skipped	fixated	skipped
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Measured on word *n*+2					
function word	identical	208 (87)	215 (60)	219 (91)	251 (91)
	nonword	209 (86)	220 (67)	214 (92)	260 (101)
content word	identical	211 (76)	212 (75)	217 (85)	259 (112)
	nonword	214 (94)	222 (71)	224 (103)	276 (112)
Measured on word *n*+1					
function word	identical	209 (67)		209 (67)	
	nonword	217 (67)		220 (73)	
content word	identical	202 (70)		202 (70)	
	nonword	209 (62)		211 (65)	
Measured on word *n*					
function word	identical	202 (65)	191 (68)	216 (76)	211 (84)
	nonword	211 (76)	193 (66)	223 (84)	212 (81)
content word	identical	206 (67)	210 (75)	230 (87)	242 (100)
	nonword	213 (72)	209 (73)	244 (101)	246 (98)

Table 2.1 Results of Experiment 1. Mean value (*M*) and standard deviation (*SD*) for each experimental condition. First fixation durations (FFDs) and gaze durations (GDs) are summarized for the pre-boundary word *n*, the post-boundary word *n*+1, and the target word *n*+2.

achieved near normal distribution (see Kliegl, Masson, & Richter, 2010) and were best meeting the model assumption of normality. Therefore, we report the statistical analyses on log-transformed dependent variables.

2.3 Results

In the following, LMMs on log-transformed GDs for each word in the three-word target region are reported. If not stated otherwise, results were comparable in the analyses on SFDs and FFDs. Table 2.1 summarizes the condition means for untransformed GDs and FFDs[2] on word *n*+2, word *n*+1, and word *n* respectively.

[2] Condition means for all tables and figures were computed over all respective data points. In ANOVAs, statistical effects are estimated on the level of aggregated condition means per subject. However, LMMs estimate fixed and random effects simultaneously from the variance of the unaggregated data. Although not identical, the condition means chosen here more closely reflect the idea of the LMM approach.

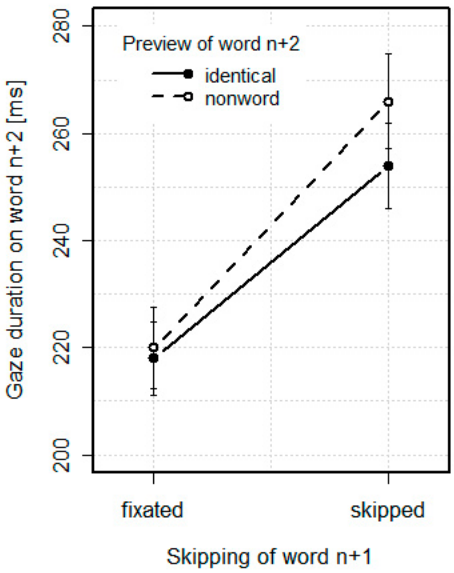

Figure 2.2 N+2 preview benefit after skipping word *n*+1. Plotted are the mean GD on the target word *n*+2 depending on the preview condition of word *n*+2 and skipping of the short post-boundary word *n*+1. Error bars represent the 95 % confidence intervals.

2.3.1 Target word *n*+2

GDs on the target word *n*+2 showed a tendency of a 5 ms PB if identical preview of word *n*+2 was available rather than denied (b = .02, SE = .01, t = 1.87). N+2 preview was not significant in SFDs and FFDs (with t = .92 and t = 1.34, respectively). The main effect of lexical status of word *n*+1 did not affect target word GDs (b = .03, SE = .02, t = 1.53). In other words, the processing difficulty of word *n*+1 did not spill over into fixation durations on the target word *n*+2. Moreover, PB on word *n*+2 was not affected by the processing difficulty of the intermediate word *n*+1 (interaction of *n*+2 preview and *n*+1 lexical status: $t < 1.02$).

If the previous word *n*+1 was skipped, GDs on the *n*+2 target increased about 41 ms relative to when word *n*+1 was fixated. This post-skipping cost was highly significant (b = .28, SE = .02, t = 17.7). More importantly, skipping word *n*+1 interacted with previewing word *n*+2 (b = .06, SE = .03, t = 2.22). As Figure 2.2 illustrates, the PB effect on word *n*+2 increased to 12 ms if word *n*+1 was skipped. If word *n*+1 was fixated, the *n*+2 PB effect in target word GDs averaged only to 2 ms. The interaction was marginally significant in SFDs (b = .05, SE = .03, t = 1.88) but not in FFDs (b = .03, SE = .02, t = 1.41). Skipping word *n*+1 further resulted in a tendency towards spillover of the *n*+1 processing difficulty in GDs on word *n*+2 (interaction of *n*+1 skipping and *n*+1 lexical status: b = -.05, SE = .03, t = -1.94). This interaction became even stronger in SFDs and FFDs on word *n*+2 (t = -3.17 and t = -2.80). No other effects were significant.

Separate LMM's were conducted conditional on whether word *n*+1 was fixated or skipped. They supported the notion that the *n*+2 PB was only significant after skipping word *n*+1 (b = .06, SE = .02, t = 2.98), not if word *n*+1 was fixated (b = -.01, SE = .02, t = -.48). In contrast, spillover of the *n*+1 processing difficulty was limited to cases in which word *n*+1 was previously fixated (b = .05, SE = .03, t = 2.07) and not skipped (b = -.002, SE = .03, t = -.08). The pattern of results was identical for FFDs and SFDs.

2.3.2 Pre-boundary word *n*

Preview of word *n*+2 significantly modulated GDs on word *n* (b = .02, SE = .01, t = 2.00). Word *n* GDs were 7 ms longer if word *n*+2 was presented as a nonword preview. This *n*+2 PoF effect was not significant in FFDs (b = .02, SE = .01, t = 1.78) but in SFDs (with t = 2.10). As can be seen in Figure 2.3, the *n*+2 PoF effect was further modulated by skipping the upcoming word *n*+1 (interaction of *n*+2 preview and *n*+1 skipping: b = -.04, SE = .02, t = -1.85). The *n*+2 PoF effect amounted to 11 ms if word *n*+1 was subsequently fixated, and there was virtually no effect if word *n*+1 was skipped. However, this interaction was not significant in SFDs and FFDs (t = -1.50 and t = -1.76).

In addition to the *n*+2 PoF effects, the significant main effect of lexical status of word *n*+1 indicated an *n*+1 PoF effect (b = .10, SE = .02, t = 4.75). Pre-boundary GDs were 35 ms longer if the upcoming word was a more difficult content word rather than an easy function word. Skipping word *n*+1 further affected word *n* GDs (b = .04, SE = .01, t = 2.97) and significantly interacted with the lexical status of word *n*+1 (b = .06, SE = .02, t = 2.64). Whereas skipping a content word *n*+1 induced on average 7 ms costs on word *n*, skipping a function word *n*+1 resulted in a 7 ms benefit prior to skipping word *n*+1.

2.3.3 Post-boundary word *n+1*

The three-letter word *n*+1 was skipped on 55 % of the cases. If word *n*+1 was not skipped, it was almost always fixated only once in a single fixation (99 %). Therefore, analyses for GDs, FFDs, and SFDs are highly redundant. Fixation durations on word *n*+1 showed a main effect of previewing word *n*+2 (b = .04, SE = .02, t = 2.86). Fixation durations were 10 ms longer if word

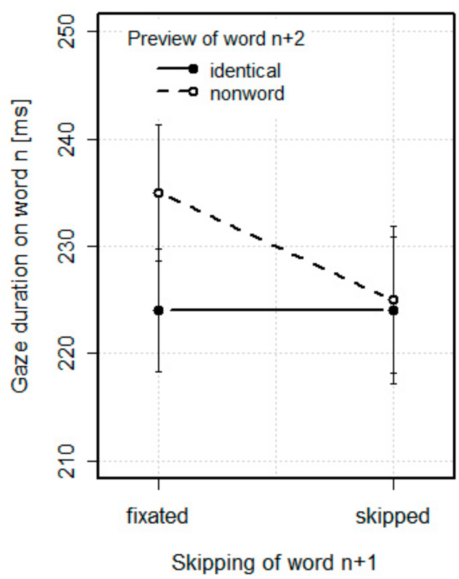

Figure 2.3 N+2 parafoveal-on-foveal effect. Plotted are the mean GDs on the pre-boundary word *n* depending on the preview condition of word *n*+2 and skipping of the upcoming word *n*+1. Error bars represent the 95 % confidence intervals.

n+2 was presented as a nonword preview. The lexical status of word *n*+1 was not significant ($b = -.03$, $SE = .02$, $t = -1.25$). Thus, there was no immediacy effect of the current *n*+1 processing difficulty in fixations on word *n*+1. The interaction of *n*+2 preview and *n*+1 lexical status was also not significant ($b = .04$, $SE = .03$, $t = 1.20$).

2.4 Discussion

The present study investigated previewing word *n*+2 in the boundary paradigm. A previous study contrasting word *n*+1 and word *n*+2 preview varying the location of the boundary had provided no significant evidence for *n*+2 preview effects (Rayner et al., 2007). The absence of *n*+2 effects had been interpreted in favor for SAS-models and against parallel distributed processing in the perceptual span. Optimizing the conditions for parafoveal processing in the *n*+2-boundary paradigm, Experiment 1 documents *n*+2 preview effects which are non-locally distributed across a three-word target region.

2.4.1 N+2 preview benefit in the *n*+2-boundary paradigm

The present study evidenced a 12 ms PB effect if the preceding word *n*+1 was skipped. Fixation durations on word *n*+2 were shorter if correct *n*+2 preview was provided throughout sentence reading rather than if preview was denied, but this was only the case if the previous word *n*+1 was skipped. Rayner et al. (2007) reported a similar trend in their data which could not be tested due to a lack of statistical power. Although significant, the present *n*+2 PB effect was quite small being only about one third of the effect size typically obtained for previewing word *n*+1 (see 1.2.2). Given that the decrease of visual acuity is gradually reducing the processing efficiency in parafoveal vision, the size of the *n*+2 PB effect might yet be a plausible value. Moreover, finding PB effects on word *n*+2 under conditions of a short three-letter word *n*+1 is consistent with the spatial extent of the perceptual span comprising 14-15 characters to the right of a given fixation (e.g., McConkie & Rayner, 1976).

PB is taken as evidence for processing a word prior to its fixation and integrating its parafoveal information across saccades. The present results suggest that parafoveal processing is not restricted to the neighboring word *n*+1 but extends up to word *n*+2, at least if word *n*+1 is short. Moreover, *n*+2 PB was restricted to cases in which word *n*+1 was skipped, a finding in agreement with McDonald (2006) who argued that preview is gained only from the saccade goal. In his study, PB was only obtained if the saccade that triggered the display change directly landed on the target word. If there was a fixation prior to the target, *n*+2 PB diminished.

The interaction of *n*+2 preview and skipping word *n*+1 was not significant in Kliegl et al. (2007), although condition means showed a similar pattern with a PB effect of 13 ms in GDs after skipping word *n*+1. In fact, in the respective study we argued that there were no effects of previewing word *n*+2 in fixation durations when the target word was finally fixated. The present results alter this conclusion.

2.4.2 Parafoveal-on-foveal effects on word *n*

There were two different PoF effects on the pre-boundary word *n*, one driven by the lexical status of the neighboring word *n*+1 and the other resulting from the preview condition of word *n*+2. First, GDs were 35 ms longer if the neighboring word *n*+1 was a more difficult content rather than an easy function word. The *n*+1 PoF effect might be the result of word *n* selectivity conditional on the syntactical constraints an upcoming content or function word implies on its preceding word. In fact, the frequency of word *n* differed with respect to whether word *n*+1 was a function or a content word ($t(79) = 2.30$, $p = .03$). Word *n* frequency was higher prior to high-frequent function words and lower before less-frequent content words (449 and 141 per million, respectively). As a consequence, the effect observed here might reflect an immediacy effect of the processing difficulty of the pre-boundary word *n* itself rather than a PoF effect of the upcoming word *n*+1.

However, including word *n* frequency as a covariate in the analysis did not change the results reported in section 2.3.2. Although there was a significant immediacy effect of word *n* frequency ($b = -.05$, $SE = .01$, $t = -5.44$), it was not involved in any further interaction (all absolute *t* values < 1.53). Moreover, the PoF effect of the lexical status of word *n*+1 was still significant ($b = .08$, $SE = .02$, $t = 3.97$). Thus, fixation durations on word *n* were directly modulated by the lexical status of the neighboring word *n*+1: A more difficult content word increased fixation durations on the prior word *n*.

Second, we found weak evidence for an additional PoF effect of word *n*+2 with 7 ms longer pre-boundary fixations if word *n*+2 was a nonword preview. As nonwords have a frequency of occurrence of (or close to) zero, they can be considered to induce high parafoveal processing difficulties. From this perspective, the *n*+2 PoF effect is concordant with the PoF effect of word *n*+1 suggesting increased foveal processing times if parafoveal word difficulties are obtained. In contrast to Kliegl et al. (2007), the size of the *n*+2 PoF effect did not depend on the lexical status of word *n*+1. The present re-analysis suggests that skipping the upcoming word *n*+1 was the real source of the interaction variance. The *n*+2 PoF effect seemed to be present only if word *n*+1 was fixated on one of the next fixations which was more likely if word *n*+1 was a content rather than a function word.

If this result is reliable, it questions the notion of obtaining preview only from the saccade goal (McDonald, 2006). It would rather indicate a tradeoff between saccade programming and fixation duration modulation. If the decision to skip word *n*+1 is taken, processing difficulties of the saccade target word *n*+2 do not further influence fixation durations on word *n* but will be expressed when word *n*+2 is fixated shortly after. If word *n*+1 is not skipped but fixated instead, fixation durations on the previous word *n* are prolonged if the parafoveal word *n*+2 preview is more difficult to process. In summary, the present results indicate that *n*+2 preprocessing does not only lead to later facilitation effects if word *n*+2 is finally fixated but can also directly modulate fixation durations when it is processed in parafoveal vision.

2.4.3 N+2 preview effects on the post-boundary word *n*+1

Fixation durations on word *n*+1 provide further evidence for previewing word *n*+2. If word *n*+1 was fixated and not skipped, there was a 10 ms effect of word *n*+2 preview on the short post-boundary word *n*+1. The direction of this *n*+2 preview effect was in agreement with both the *n*+2 PB effect and the *n*+2 PoF effect: Fixation durations on word *n*+1 were shorter if word *n*+2 had been presented as the identical preview and longer if word *n*+2 was the nonword preview. However, it has to be noted that the saccade prior to fixating word *n*+1 crossed the boundary and triggered the display change of word *n*+2. Thus, during fixating word *n*+1, word *n*+2 always was the identical target word, however, now previewed as a direct *n*+1 neighbor.

Three interpretations of this *n*+2 preview effect on word *n*+1 are possible. First, changing the *n*+2 display from a nonword to the target might be perceptually disruptive, interrupting saccadic programming, and thus prolonging the first fixation duration after crossing the boundary (e.g., O'Regan, 1990). Such visual effects were systematically investigated in a study by Inhoff, Starr, Liu, and Wang (1998) who varied, for example, the monitor's refresh rate to induce flicker during display changes. The impact of such variables showed to be no viable source for *n*+1 PB effects in the boundary paradigm. Based on these results, it can be argued that the display changes in the present experiment should also not exert any perceptual disruption. In fact, none of the participants reported to have noticed any display changes when asked after the experiment was finished. However, the present data allow no independent test of this hypothesis (but see 4.5.1).

Second, in line with the mislocated-fixation hypothesis (see 1.2.3), the *n*+2 preview effect on word *n*+1 could reflect an *n*+2 PB effect in fixations that fell short of their intended target word *n*+2. Given that short words are intended to be skipped quite frequently (e.g., Brysbaert & Vitu, 1998; Drieghe, Brysbaert, Desmet, & DeBaecke, 2004), some proportion of *n*+1 fixations may actually be targeted to word *n*+2, but due to failed skipping are observed on word *n*+1. Such mislocated fixations – if not immediately corrected – should then reflect processing the attended rather than the fixated word. It could be argued that any disadvantages resulting from *n*+2 preview denial were compensated for in such mislocated fixation(s) on word *n*+1. This interpretation would also be consistent with the finding that PB effects on word *n*+2 were almost absent if word *n*+1 was previously fixated.

Third, the effect could also be a delayed *n*+2 PoF effect spilling over from word *n* into fixations on word *n*+1. Given the distance of word *n*+2 from pre-boundary fixations, the availability of processing difficulties of word *n*+2 might be delayed (Lee, Legge, & Ortiz, 2003) leading to later effects than processing difficulties of the neighboring word *n*+1. Foreshadowing some of the upcoming results, this would be a parsimonious explanation for the consistent finding of *n*+1 PoF effects and inconsistent *n*+2 PoF effects on word *n*. In most cases, the *n*+2 PoF effect comes in delayed and prolongs the next fixation after the boundary, which often is on the next word *n*+1.

An *n*+2 preview effect in fixation durations on the pretarget word *n*+1 has also been documented in an *n*+2-boundary paradigm reading Chinese (Yang, Wang, Xu, & Rayner, 2009). Notwithstanding the fact that there might be substantial differences between processing a character-based script such as Chinese and alphabetic languages such as German or English (e.g., Yan, Kliegl, Richter, Nuthmann, & Shu, 2010), this effect emphasizes an interesting new property of the *n*+2-boundary paradigm. The fact that the locations for PoF and PB effects are separated by an intermediate word *n*+1 allows a more detailed investigation of the dynamics of parafoveal processing inside the perceptual span during reading. The experiments in Chapter 4 will give an example of how this can be utilized to approach more theoretical questions of dissociating the distributed sources of *n*+2 preview effects in the perceptual span.

2.4.4 Conclusions

Under optimal conditions of a short word *n*+1, parafoveal processing in the perceptual span seems to extend up to word *n*+2. The effects of preprocessing word *n*+2 during pre-boundary fixations were expectedly small and seem to be distributed across several words in the target region. We obtained weak evidence for an immediate *n*+2 PoF effect on the pre-boundary word *n* and later preview effects if the pretarget word *n*+1 or the target word *n*+2 was fixated.

Such non-local effects are consistent with the notion of distributed attention enabling parallel lexical processing of all words in the perceptual span. As processing is graded with decreasing efficiency in parafoveal vision, *n*+2 effects are expected to be smaller than preview effects of the neighboring word *n*+1. Due to parallel lexical processing, parafoveal word difficulties may further interfere with foveal word processing resulting in PoF effects. Moreover, each saccade shifts the processing gradient to a new location and permits word *n*+2 to be parafoveally processed from a closer fixation position. Thus, the fact that *n*+2 PB effects seemed to be compensated for in fixations prior to the target word is in agreement with PDA models. Likewise, if word *n*+1 is skipped and word *n*+2 is directly fixated after crossing the boundary, *n*+2 fixation durations should reflect stronger preview effects than if word *n*+1 is fixated first prior to fixating word *n*+2.

Rayner et al. (2007; footnote 1) argued that the default situation in SAS models limits parafoveal processing to the neighboring word *n*+1. However, optimizing the conditions for previewing word *n*+2 in the present study may have facilitated early attention shifts up to word *n*+2 while the eyes still fixate on word *n* (Pollatsek, Reichle, & Rayner, 2006). This notion is supported by the fact that *n*+2 PB effects were evident only if word *n*+1 was skipped compatible with complete parafoveal processing of word *n*+1 prior to attention shifts onto word *n*+2. More difficult to explain are the *n*+2 preview effects prior to the target word *n*+2. In SAS models, such early preview effects are attributed to oculomotor error leading to mislocated fixations on a word prior to the word that is effectively attended and processed. Whether this is a viable explanation will be investigated in Chapter 4. At this point, we provided first evidence for previewing words up to word *n*+2 under such optimized conditions as described here. The experiments in the next chapters will follow up on these results in more detail.

CHAPTER 3

REPLICATING N+2 PREVIEW EFFECTS IN AN AGE-COMPARATIVE STUDY: EXPERIMENT 2

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Experiment 1 first documented effects of previewing word *n*+2 in an *n*+2-boundary paradigm reading alphabetic script (i.e., German). Although significant, the *n*+2 effects were quite small. Given the gradual decrease of visual acuity and processing efficiency in parafoveal vision, the observed size may yet be realistic and not spurious. Therefore, one goal of the present study was to test the reliability of the small *n*+2 effects and to replicate our previous findings. Second, we were interested in age differences in parafoveal processing inside the perceptual span with age likely representing a limiting condition for word *n*+2 processing. Therefore, we tested both young and older adults with the *n*+2-boundary paradigm.

3.1 Age differences in the perceptual span during reading

Reading is a highly practiced skill, acquired early in life and executed daily throughout the lifespan. Comparisons of young and older adults' eye movements in reading, so far, revealed more similarities than it disclosed differences. However, older adults read somewhat more slowly with longer fixation durations on the words they fixate. In addition, they skip words more often and perform more regressions back into regions they already inspected (Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner, Reichle, Stroud, Williams, & Pollatsek, 2006). Increased word skipping in older adults has been interpreted as a more risky strategy probably adopted to compensate for their overall slowed-down reading rate (O'Regan, 1990). Older adults might engage more in top-down processing such as guessing the upcoming word on (partial) information perceived from not-yet-fixated words in parafoveal vision (Rayner et al., 2006).

Another related factor may be that visual acuity decreases with increasing age. Research on visual search revealed that older adults have pronounced difficulties in processing foveal but also non-foveal information compared to their younger controls (Cerella, 1985; Collins, Brown, & Bowman, 1989; Scalfia, Thomas, & Joffe, 1994; but see Coeckelbergh, Cornelissen, Brouwer, & Kooijman, 2004, for a different result). From such a perspective, increased word skipping rates of older adults could also be understood as a strategy to compensate for the age-related acuity loss in parafoveal vision. If the ultimate goal changes to move not-inspected parts of text closer to the region where resolution is highest then older adults might increase their average saccade amplitudes concurrently resulting in a higher word skipping probability than younger adults. However, such age differences are further pronounced with increasing attentional task demand (e.g., Sekuler & Ball, 1986; Scialfa, Kline & Lyman, 1987) and can be compensated with practice (Ball, Beard, Roenker, Miller, & Griggs, 1988). Thus, aging seems to go beyond pure sensory deficits also leading to age-related cognitive limitations, a finding which might well translate to reading.

Both perceptual and attentional factors have shown to play a role in the size of the perceptual span in reading (see 1.1.2). Therefore, a first step in understanding possible age-differential effects in reading is to determine whether, and if so how, young and older adults differ in their perceptual spans. Rayner, Castelhano, and Yang (2009) recently reported a more symmetric perceptual span for older readers compared to the known asymmetry in young adults. Using the moving-window paradigm, Rayner et al. showed that older readers' perceptual span was reduced into the direction of reading relative to younger adults. Given a fixation on word *n*, younger adults benefited from additional information of both parafoveal words *n*+1 and *n*+2 (i.e., with a three-word window). In contrast, older adults showed no performance decrements when word *n*+2 was denied and only word *n* and the neighboring word *n*+1 were visible (i.e., with a two-word window). In addition, they relied more on information of the word to the left of fixation.

Following up on the reduced perceptual span in older adults, Rayner, Castelhano, and Yang (2010) further investigated the amount of preview older and younger readers extract from a parafoveal word *n*+1 in the boundary paradigm. In agreement with previous research, they observed a PB effect on the target word *n*+1. Moreover, PB was smaller for older readers, although not significant in all fixation duration measures. There was no PoF effect of previewing word *n*+1 in pre-boundary fixations on word *n*, neither for young nor for older adults. The age-reduced *n*+1 PB effect corroborates the finding of an age-related reduction in the perceptual span size. The absence of PoF effects for both age groups, however, relates to the more general debate on the time course of processing inside the perceptual span (see Chapter 4).

3.1.1 Possible age effects in processing word *n*+2

As the perceptual span was estimated to incorporate the neighboring word *n*+1 in both age groups (Rayner et al., 2009), testing PBs from parafoveal words that designate the spatial limits of the perceptual span might even show more consistent age effects. The spatial limits of parafoveal processing in young adults were first investigated by Rayner et al. (2007) using the *n*+2-boundary paradigm. As mentioned above, they did not find any evidence for parafoveal processing of the target word *n*+2, neither a PB effect on word *n*+2 nor any other effects in the pretarget region (see also Angele et al., 2008, and Angele & Rayner, 2011, for similar results using a slightly different paradigm). The results in the *n*+2-boundary paradigm contrast with those of Rayner et al. (2009) who reported that younger adults slowed their reading speed if word *n*+2 information was denied. The latter finding clearly suggests that preview of word *n*+2 was effectively used and is in agreement with the results of Experiment 1 (see Chapter 2).

Given the results from the moving-window study for the older readers one might argue, on the one hand, that *n*+2 effects should not be obtained for older adults. On the other hand, one could also argue that investigating parafoveal processing of word *n*+2 in a well-controlled setting such as the *n*+2-boundary paradigm increases the chance of finding *n*+2 preview effects even for older adults. In the moving window paradigm, every word in the sentence can become a possible word *n*+1 relative to the currently fixated word *n*. As word lengths vary within a sentence, word *n*+2 will often be deferred further into parafoveal vision. In contrast, in the *n*+2-boundary paradigm word length of the pretarget word *n*+1 is controlled to minimize the distance between the pre-boundary fixation and the target word *n*+2.

The goal of the present study was to investigate age differences in parafoveal processing under conditions of the *n*+2-boundary paradigm. Therefore, we compared young and older adults using an experimental setup identical to Experiment 1 (see Chapter 2). If older adults' perceptual spans are more symmetric and significantly reduced in the direction of reading, they should exhibit no or much weaker effects of manipulating preview of word *n*+2 than young adults. Similarly, PoF effects of word *n*+1 should be attenuated for them as well. Formulated from the perspective of young adults, if their perceptual span is more asymmetric than that of older adults comprising the two parafoveal words *n*+1 and *n*+2, they should exhibit effects of previewing word *n*+2 somewhere within the three-word target region.

3.2 Method

3.2.1 Participants

Forty young and 40 older adults participated in the present study. Young adults were 9 male and 31 female Potsdam University students (age: M = 23 years, SD = 4) receiving either course credit or 7 € for their one-hour participation. Older adults were 17 male and 23 female members of the Potsdam community (age: M = 71 years, SD = 4) who were paid 10 €. All participants provided informed consent before the start of the experiment.

Subjects wore their glasses to achieve corrected-to-normal vision. Old adults' visual acuity corresponded on average to the normal 20/20 Snellen ratio (M = 1.01, SD = 0.49), but young adults typically reached higher than normal values (M = 1.36, SD = 0.40). Based on acuity data for 30 of 40 old and 13 of 40 young adults, the older participants visual acuity was significantly reduced ($t(41) = 2.44$, $p < .05$). The two groups showed the usual pattern of higher scores for young than older adults in a psychometric measure of processing speed (Tewes, 1991; young: $M = 61$, $SD = 10$; old: $M = 48$, $SD = 7$; $t(65) = 6.42$, $p < .001$) and slightly but significantly higher scores for older than young adults in a test of vocabulary (Schmidt & Metzler, 1992; young: $M = 32$, $SD = 2$; old: $M = 33$, $SD = 2$; $t(75) = -3.23$, $p < .01$). Psychometric data were missing from three young adults but were available for all 40 older adults.

3.2.2 Sentence material, apparatus, and procedure

The same sentence material was used as in Experiment 1 (see 2.2.2). Both young and older adults were tested with the same apparatus and procedure as described in section 2.2.3.

3.2.3 Data selection and analysis

Data from two young adults were excluded from analyses, one set of data due to technical problems during recording, and the other set because the subject reported to have noticed some display changes during the experiment. For the second reason, we also excluded two older adults. From the remaining 38 young and 38 older adults, 11% of the sentences were lost due to blinks and signal losses. Binocular saccades were detected offline using the algorithm introduced by Engbert and Kliegl (2003; modified by Engbert & Mergenthaler, 2006). While reading was binocular, only right-eye data were analyzed. As detailed in 2.2.4, data were selected on two levels: On the sentence level, 18 % of sentences were excluded due to invalid display changes. Further considering invalid fixations, a total of 40 % of the recorded word-based fixations in the target region were excluded (33 % for word *n*, 53 % for word *n*+1, 39 % for word *n*+2). This still left 6,896 valid GDs on word *n*, 3,289 on word *n*+1, and 5,988 on word *n*+2.

As in Experiment 1 (see 2.2.5), separate LMM's were estimated for each of the three words in the target region. Age group was specified as a between-subjects factor (young vs. older adults). The experimental variables such as preview of word *n*+2 (identical vs. nonword preview) and the lexical status of word *n*+1 (function word vs. content word) were included as within-subject factors. Skipping of word *n*+1 (fixated vs. skipped) was again included for LMM's of the pre-boundary word *n* and the target word *n*+2. Participants, unique words, and sentences (items) were included as random factors. For each analysis we report the regression coefficients (*b*), the standard errors (*SE*s) and *t* values. A fixed effect is considered significant with absolute *t* values > 2.0 reflecting at least two *SE*s. Fixation durations were log-transformed to achieve near normal distribution of the dependent variables.

3.3 Results

Table 3.1 provides summary statistics for each experimental condition for young and older adults,

Young adults		FFD		GD	
		Skipping word *n*+1		Skipping word *n*+1	
Lexical status of word *n*+1	Preview of word *n*+2	fixated	skipped	fixated	skipped
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Measured on word *n*+2					
function word	identical	198 (74)	220 (59)	210 (87)	248 (84)
	nonword	190 (62)	226 (65)	195 (69)	266 (86)
content word	identical	216 (84)	206 (65)	226 (98)	242 (95)
	nonword	216 (81)	221 (69)	223 (89)	266 (107)
Measured on word *n*+1					
function word	identical	211 (72)		211 (73)	
	nonword	217 (79)		218 (79)	
content word	identical	209 (65)		209 (65)	
	nonword	215 (63)		217 (65)	
Measured on word *n*					
function word	identical	206 (53)	197 (59)	217 (72)	211 (76)
	nonword	204 (61)	196 (59)	217 (79)	214 (78)
content word	identical	216 (65)	212 (77)	253 (98)	250 (109)
	nonword	210 (64)	214 (73)	248 (99)	251 (112)

Table 3.1 Results of Experiment 2. Mean value (*M*) and standard deviation (*SD*) for young adults (above) and older adults (below). First fixation duration (FFD) and gaze duration (GD) are summarized for the pre-boundary word *n*, the post-boundary word *n*+1, and the target word *n*+2.

Older adults		FFD		GD	
		Skipping word *n*+1		Skipping word *n*+1	
Lexical status of word *n*+1	Preview of word *n*+2	fixated	skipped	fixated	skipped
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Measured on word *n*+2					
function word	identical	216 (92)	238 (81)	229 (107)	266 (103)
	nonword	209 (83)	243 (82)	219 (98)	276 (113)
content word	identical	234 (93)	213 (73)	243 (101)	243 (103)
	nonword	238 (94)	229 (80)	245 (98)	267 (126)
Measured on word *n*+1					
function word	identical	238 (92)		239 (94)	
	nonword	232 (79)		235 (80)	
content word	identical	232 (87)		234 (91)	
	nonword	240 (88)		241 (88)	
Measured on word *n*					
function word	identical	228 (74)	219 (79)	241 (85)	239 (96)
	nonword	227 (74)	221 (79)	242 (93)	241 (95)
content word	identical	235 (87)	215 (72)	265 (108)	256 (113)
	nonword	234 (84)	214 (76)	265 (112)	249 (107)

respectively. Results from the LMMs are described for each of the three target words separately. First, we refer to the effects from the experimental variables, listing the additional age-differential effects in a separate paragraph.

3.3.1 Target word *n*+2

Experimental effects. As illustrated in Figure 3.1, the benefit of previewing word *n*+2 was 18 ms when word *n*+1 was skipped but decreased to a 5 ms preview cost when word *n*+1 was fixated (interaction of *n*+2 preview and *n*+1 skipping; GD: b = .07, SE = .02, t = 4.10; FFD: b = .04, SE = .02, t = 2.40; SFD: b = .04, SE = .02, t = 2.52). The main effects contributing to this interaction were also significant, both the *n*+2 PB (GD: 6 ms, b = .03, SE = .01, t = 3.28; FFD: 4 ms, b = .02, SE = .01, t = 2.60; SFD: 3 ms, b = .02, SE = .01, t = 2.93) and the cost for skipping word *n*+1 (GD: 35 ms, b = .25, SE = .01, t = 25.2; FFD: 9 ms, b = .11, SE = .01, t = 11.8; SFD: 12 ms, b = .15, SE = .01, t = 14.7). The size of the *n*+2 PB effect depended also on the processing difficulty of word *n*+1. The benefit of previewing word *n*+2 amounted to 4 ms after function words *n*+1 and increased to 9 ms after content words (interaction of *n*+2 preview and *n*+1 lexical status; GD: b = .04, SE = .02, t = 2.13; FFD: b = .04, SE = .02, t = 2.50; with only a tendency in SFDs: b = .03, SE = .02, t = 1.87). Spillover of *n*+1 processing difficulty on the target word *n*+2 was also significant as a main effect in GDs (b = .03, SE = .02, t = 2.02), but only showing a trend in FFDs (b = .02, SE = .01, t = 1.80) and SFDs (b = .03, SE = .01, t = 1.91). Finally, skipping cost on word *n*+2 was larger after easy function words rather than difficult content words *n*+1 (interaction of *n*+1 skipping and *n*+1 lexical status; GD: b = -.13, SE = .02, t = -7.52; FFD: b = -.16, SE = .02, t = -9.80; SFD: b = -.18, SE = .02, t = -10.1). The three-factor interaction involving all experimental variables was not significant (with all absolute t < .41). Main effects of skipping cost and spillover of processing difficulty are well established by previous research. The more

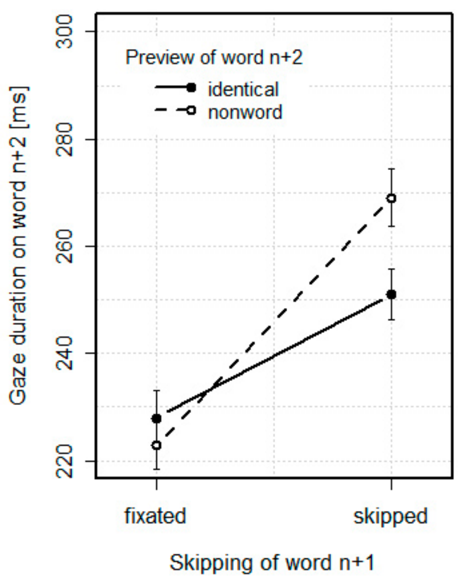

Figure 3.1 N+2 preview benefit after skipping word *n*+1. Plotted are the mean GDs on the target word *n*+2 depending on the preview condition of word *n*+2 and skipping of the short post-boundary word *n*+1. Error bars represent the 95 % confidence intervals.

important result is the reliable *n*+2 PB effect after skipping of word *n*+1 shown in Figure 3.1, replicating the results from Experiment 1 (see Chapter 2).

Age effects. The significant *n*+2 PB when word *n*+1 was skipped was not further modulated by age. Neither the critical three-factor interaction (GD: b = -.05, SE = .03, t = -1.37; FFD: b = -.02, SE = .03, t = -.05; SFD: b = -.04, SE = .03, t = -1.22) nor the subordinate two-factor interaction of age group and *n*+2 preview (GD: b = -.004, SE = .02, t = -.23; FFD: b = .01, SE = .02, t = .03; SFD: b = -.01, SE = .02, t = -.37) was significant. In fact, post-hoc contrasts in the LMM for the *n*+2 PB effect conditional on skipping word *n*+1 nested within age groups revealed that both young and older adults showed significant *n*+2 PB if word *n*+1 was skipped. Young adults showed a 20 ms *n*+2 PB effect after skipping word *n*+1 (GD: b = .07, SE = .02, t = 4.06; FFD: 9 ms, b = .04, SE = .02, t = 2.60; SFD: 11 ms, b = .04, SE = .02, t = 2.60) which reduced to a non-significant 9 ms preview cost if word *n*+1 was fixated (GD: b = -.02, SE = .02, t = -.96; FFD: 4 ms, b = -.004, SE = .02, t = -.03; SFD: 3 ms, b = -.004, SE = .02, t = -.03). Older adults' PB effect was 16 ms after skipping word *n*+1 (GD: b =.05, SE = .02, t = 2.62; FFD: 8 ms, b =.04, SE = .02, t = 2.30; with only a trend in SFDs: 7 ms, b =.03, SE = .02, t = 1.80) and not significant if word *n*+1 was fixated (GD: b = -.01, SE = .02, t = -.56; FFD: b = .003, SE = .02, t = .02; SFD: b = .001, SE = .02, t = .03). No other effects reached significance (all absolute t values < 1.81).

Older adults' GD on the target word *n*+2 were on average 14 ms longer than those of young adults, but this main effect was not significant (b = .04, SE = .04, t = 1.13; FFD: 17 ms, b = .05, SE = .03, t = 1.60; SFD: 15 ms, b = .04, SE = .03, t = 1.22). The main age-differential result was

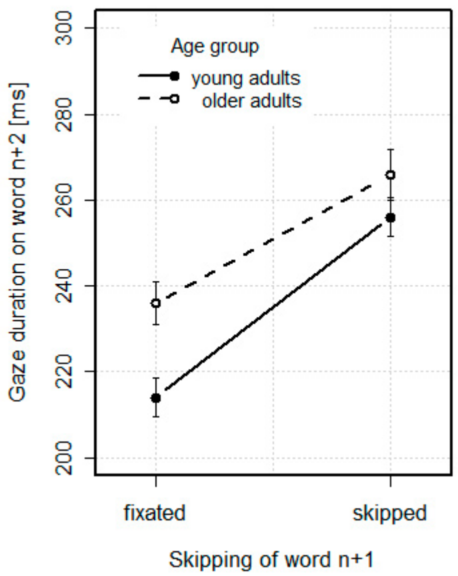

Figure 3.2 Age differences in post-skipping cost. Plotted are the mean GDs on the target word *n*+2 conditional on skipping the preceding word *n*+1, both for young and older adults. Error bars represent the 95 % confidence intervals.

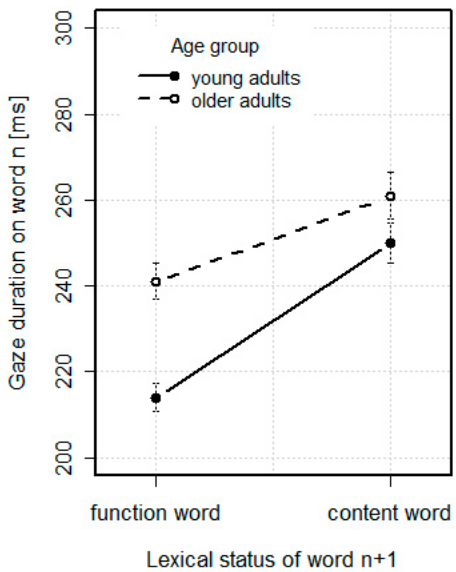

Figure 3.3 Age differences in the *n*+1 parafoveal-on-foveal effect. Plotted are the mean GDs on the pre-boundary word *n* depending on the processing difficulty of word *n*+1, both for young and older adults.

significantly smaller *n*+1 skipping cost for older than young adults (interaction of age group and *n*+1 skipping; GD: b = -.06, SE = .02, t = -3.36; marginally in SFDs: b = -.04, SE = .02, t = -1.96; but not in FFDs: b = -.005, SE = .02, t = -.03). This interaction is shown in Figure 3.2. Older adults appear to not modulate their fixation durations as strongly as young adults conditional on whether word *n*+1 was fixated or skipped. In summary, age revealed no reliable influence on previewing word *n*+2, which in turn was strongest if word *n*+1 was skipped. It is important to emphasize that this lack of an age difference occurred in the presence of a significant PB effect for older adults.

3.3.2 Pre-boundary word *n*

Experimental effects. GDs on word *n* were 28 ms longer when the upcoming word *n*+1 was a low-frequent content rather than a high-frequent function word (b = .11, SE = .02, t = 5.48; FFD: 9 ms, b = .04, SE = .01, t = 2.63; SFD: 12 ms, b = .06, SE = .02, t = 3.69). This is a PoF effect of the processing difficulty of word *n*+1, measured in fixations on the pre-boundary word *n*. Skipping the upcoming word *n*+1 significantly modulated pre-boundary GDs (b = .04, SE = .01, t = 4.44; FFD: b = -.02, SE = .01, t = -2.18; but not in SFDs: b = -.01, SE = .01, t = -1.18) and further interacted with the lexical status of word *n*+1 (GD: b = .04, SE = .02, t = 2.56; but only marginal in FFDs and SFDs: b = .03, SE = .01, t = 1.96 and b = .03, SE = .01, t = 1.85, respectively). Word *n* GDs prior to function words were 229 ms if word *n*+1 was then fixated and 226 ms if it was skipped. For content words *n*+1, this skipping benefit on word *n* was slightly larger amounting to 7 ms. Finally, there was no evidence for an *n*+2 PoF effect (with all absolute t values < .45).

Age effects. Older adults' GDs were 18 ms longer on the pre-boundary word *n* than those of young adults; again, not resulting in a significant age effect (b = .06, SE = .04, t = 1.52). SFDs and FFDs indicated a tendency towards an age main effect (with t = 1.88 and t = 1.81). Fixation durations on the pre-boundary word *n* revealed the following age-differential effect: the PoF effect of the upcoming word *n*+1 was more pronounced in young than in older adults (b = -.06, SE = .02, t =-3.87; FFD: b = -.04, SE = .01, t = -3.20; SFD: b = -.04, SE = .01, t = -2.91). As can be seen in Figure 3.3, this was mainly due to older adults showing a disproportionate increase in their GDs prior to an easy function word *n*+1.

For completeness, there was an additional age-effect in FFDs: Young adults showed skipping benefits prior to function words and no difference prior to content words, whereas older adults showed even stronger skipping benefits prior to content words (b = -.07, SE = .03, t = -2.75; for GDs and SFDs both absolute t values < 1.48). No other effects were reliable (all absolute t values < 1.73).

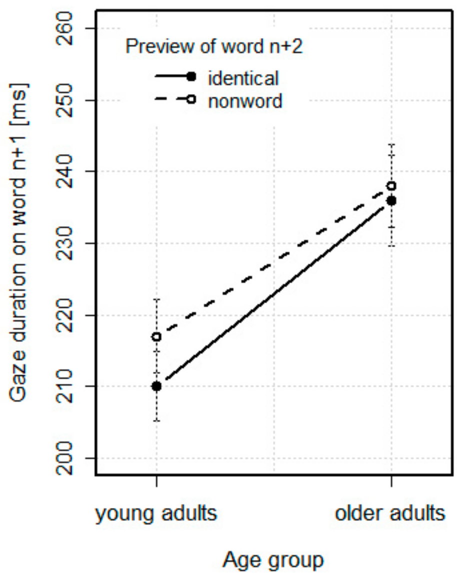

Figure 3.4 N+2 preview effect on the post-boundary word *n*+1. Plotted are the mean GDs on word *n*+1 conditional on the preview condition of word *n*+2 for young and older adults. Error bars represent the 95 % confidence intervals.

3.3.3 Post-boundary word *n*+1

Experimental effects. Skipping of word *n*+1 amounted to 56 %. If word *n*+1 was fixated, it was fixated with a single fixation in 99 %. Therefore, analysis of GDs resembles the results of SFDs and FFDs and only the results for GDs will be reported. There was a main effect of previewing word *n*+2 in fixation durations on the post-boundary word *n*+1 (b = .04, SE = .01, t =3.69). Fixation durations on word *n*+1 were 4 ms longer if word *n*+2 was presented as the incorrect nonword preview during pre-boundary fixations. The immediacy effect of the lexical status of word *n*+1 was far from being significant (b = -.01, SE = .03, t =-.20) and did not interact with preview of word *n*+2 (b = .03, SE = .02, t =1.47).

Age effects. Fixation durations on word *n*+1 were 23 ms longer for older than young adults (b = .08, SE = .04, t = 2.08). The interaction between age group and *n*+2 preview was not significant (b = -.02, SE = .02, t = -1.01). Nevertheless, as illustrated in Figure 3.4, the *n*+2 preview effect was numerically larger for young than for older adults. Post-hoc LMMs for the two age groups suggested that for young readers the 8 ms *n*+2 preview effect on word *n*+1 was significant (b = .05, SE = .01, t = 3.41), but the 3 ms effect for older readers was not (b = .03, SE = .02, t = 1.72). With all precaution due to the absence of an age group by *n*+2 preview interaction, the pattern, again, is consistent with reduced flexibility of older adults' GDs with respect to non-local processing demand. There were no further significant effects (all absolute t values < 1.47).

3.4 Discussion

We investigated age differences in the perceptual span during reading under highly controlled conditions in the *n*+2-boundary paradigm. Given a significant age-reduction in the older adults' span size (Rayner et al., 2009) and previous evidence for *n*+2 preview effects for young adults (see Chapter 2) the hypotheses were straightforward: Testing the limits of parafoveal information extraction, younger adults should benefit from previewing word *n*+2 whereas older adults should not. Besides some weak evidence for generally longer fixation durations in the older readers (Kliegl et al., 2004; Rayner et al., 2006), we found significant PB on the target word *n*+2 for both age groups. The apparent age invariance in the size of the perceptual span (given a short word in position *n*+1) was further corroborated by older adults showing decreased rather than increased "cost" on word *n*+2 if word *n*+1 was skipped. Age effects were, however, evident in the size of the PoF effect of word *n*+1 in pre-boundary fixations on word *n*.

3.4.1 Age invariance in the rightward extent of parafoveal processing

With increasing age, visual acuity seems to decrease disproportionately for peripheral vision relative to regions that are closer to the location that is fixated (e.g., Cerella, 1985). In addition, older adults spend somewhat more time in fixating on words (Kliegl et al., 2004; Rayner et al., 2006), possibly reflecting older adults' additional processing demand for encoding a word in foveal vision. The well-established asymmetry of the perceptual span during reading implicates a further contribution of attentional processes, again a domain in which age differences are the rule. Thus, age differences in visual and attentional processing both predict a reduction of the older adults' span size in the direction of reading.

In contrast to this prediction, in the present Experiment 2, there was no reliable support for the expectation that older readers were less sensitive to parafoveal information of word *n*+2 than young readers. In fact, older adults exhibited the same amount of PB on the target word *n*+2 than young adults. As word *n*+2 was only separated by a three-letter word from the current fixation, *n*+2 was still in the parafoveal range with possibly negligible effects of age-related differences in eccentricity-related drop of visual acuity. The *n*+2 PB was again quite small. However, given the previous findings in Experiment 1 (see Chapter 2), the size of the *n*+2 effect in the present study is yet a plausible value. As such effects have not been found in other studies (Angele & Rayner, in press; Angele et al., 2008; Rayner et al., 2007), replicating *n*+2 preview effects for two age groups was an important goal in itself and will be discussed in more detail below (see 3.4.3).

Older adults' preserved processing of word *n*+2 was also indicated in their comparatively small skipping cost on word *n*+2. Longer fixation durations after skipping the previous word are typically attributed to reduced preview during the last fixation prior to skipping (Vitu, McConkie, Kerr, & O'Regan, 2001; Radach & Heller, 2000; McDonald, 2005; Reichle et al., 2003). If older adults had a smaller span size and thus a disadvantage in processing the parafoveal word *n*+2, this should result in larger rather than smaller post-skipping cost on word *n*+2 compared to young adults. In contrast to a parafoveal processing deficit, the age-differential reduction in skipping cost could reflect a lack of resilience in older adults' modulation of fixation durations in response to distributed processing demand during reading. Younger adults might adapt flexibly to the processing facilitation of word *n*+2 if word *n*+1 was previously fixated while older adults more or less keep their fixation pace irrespective of the local facilitation when additional preview of word *n*+2 had been available. Thus, we propose that there may not be much of an age difference in the rightward extent of the perceptual span, but there may be an age difference in the functional range of fixation durations that are deployed to respond to processing demands or processing opportunities in the perceptual span. We further elaborate on this proposal in the next section (see 3.4.2).

The present research was partly motivated by two earlier studies on age differences in the perceptual span. The lack of an age difference in processing the parafoveal word *n*+2 differs from recent findings in a moving-window experiment (Rayner et al., 2009) where older adults did not benefit from the availability of word *n*+2. Since the length of word *n*+1 varied widely in the Rayner et al. experiment, word *n*+2 was much more likely to fall outside the perceptual span than in the present study where word *n*+1 was always three letters long. In this condition, both older and young adults showed some benefit of previewing word *n*+2. The present results suggest that the word metric by itself does not adequately characterize age differences in the size of the perceptual span; it probably needs to be described both in terms of number of words and number of letters.

The comparable *n*+2 PB for older and for young readers is also difficult to reconcile with a smaller *n*+1 PB effect in older adults' GDs as reported by Rayner et al. (2010). Since word *n*+1 is even closer to the pre-boundary fixation, age-related differences should be more pronounced for previewing word *n*+2 than word *n*+1. In the present study, we used long pre-boundary words *n* to increase the likelihood of fixations and to ensure previewing the target word as an *n*+2 preview. Indeed, the word length eliminated the typical age difference in skipping word *n*, which is generally higher in older than in young adults (Laubrock, Kliegl, & Engbert, 2006; Rayner et al., 2006). Rayner et al. (2010) also reported an overall age difference of 5% in skipping. If older adults skipped the pre-boundary word *n* more often by this amount than the young adults, the *n*+1 PB may have collated with some proportion of *n*+2 preview. Age differences in pre-target skipping rates could have compromised the otherwise equally effective preprocessing of word *n*+1 between age groups. The absolute although non-significant effect size of 11 ms for the older adults' *n*+1 PB effect is in the range of the 6 ms *n*+2 PB effect we obtained in the present experiment.

In summary, given a three-letter word *n*+1, we found no evidence for an age-related reduction of the perceptual span in the *n*+2-boundary paradigm. Older adults' acuity deficits seem to affect the size of the perceptual span in reading to a much lesser degree than has been suggested from earlier research, at least in the range tested here. This may reflect that the perceptual span in reading is more closely related to attention (Engbert & Kliegl, in press; Henderson & Ferreira, 1990; Rayner & Pollatsek, 1987) than it is to physiological constraints of visual acuity. Its size might determine the area across which attention is distributed or shifted during reading, maybe to compensate for potential parafoveal acuity limitations. However, acuity limitations in the perceptual span nevertheless play a role. The size of the *n*+2 PB effect was only about one third of what is typically found in the *n*+1-boundary paradigm. Thus, parafoveal processing of word *n*+2 is less efficient than for the neighboring word *n*+1 supporting the general notion of decreasing visual acuity and processing efficiency with increasing eccentricity from the fixation position.

3.4.2 Age-related differences in the modulation of fixation durations

Processing of parafoveal words can manifest itself at two locations, both as a PB linked to the target word after the boundary and as a PoF effect on the pre-boundary word. Although we found no significant age differences in the PB on word *n*+2, older adults exhibited a weaker PoF effect of word *n*+1 in fixation durations on the pre-boundary word *n*. At first, this finding seems to contradict the age insensitivity in word *n*+2 preprocessing. We propose, however, that this counterintuitive effect pattern is due to two qualitatively different phenomena of parafoveal processing. In fact, PB is assumed to reflect facilitation due to integrating parafoveally extracted information into later identification processes when a saccade eventually moves the word into foveal vision (Inhoff, 1990; Inhoff & Tousman, 1990). It may reflect a highly automatic process, similar to small or even absent age differences documented for lexical processing (e.g., Lima, Hale, & Myerson, 1991; Mayr & Kliegl, 2000). In contrast, PoF effects are often interpreted in terms of cross-talk due to overlap in parafoveal and ongoing foveal word recognition processes (Kennedy, 1998, 2000).

From this latter view, the present results seem to indicate that older adults utilize parafoveal information up to word *n*+2 as good as young adults, but that older adults suffer stronger interference from processing words in parafoveal vision, paradoxically from easy function words *n*+1. An alternative perspective is that previewing difficult content words in position *n*+1 affects young adults' foveal word *n* processing more strongly than that of older adults. The smaller PoF effect of older adults can, therefore, be again construed as a lack of resilience in adjusting fixation durations to distributed processing demands, here in adjusting towards parafoveal processing difficulties.

There is another piece of evidence in support of this interpretation. Although the effect was only significant in a post-hoc analysis, identical preview of word *n*+2 shortened fixations on word *n*+1, and the amount of shortening was smaller for older than for young adults. Besides replicating the *n*+2 preview effect on the short post-boundary word *n*+1 first documented in Experiment 1 (see Chapter 2), the tendency towards an age-related reduction of this effect is compatible with the proposition of an age-differential lack of resilience. Older adults may not exploit the processing opportunity to the same extent as young adults.

The proposal of an age-related lack of resilience in modulating fixation durations in response to processing opportunities in the perceptual span is based on three non-canonical age by condition interactions observed in Experiment 2. This interpretation can also be linked to an age difference in the inhibition parameter of the SWIFT model (Laubrock et al., 2006). In this study, the authors argued that weaker inhibition in older adults leads to less modulation in their fixation durations compared to young adults. In turn, this age difference is also roughly compatible with the assumption of impaired inhibitory control processes with aging (Hasher Stoltzfus, Zacks, & Rypma, 1991) and thus with assumptions of stronger interference of distracting information in older adults.

3.4.3 Replicating preview effects in the *n*+2-boundary paradigm

Evidence of preprocessing word *n*+2 is by itself not uncontroversial. In the present study, we observed *n*+2 preview effects across two age groups and, therefore, replicated important findings from Experiment 1 (see Chapter 2). However, some results also slightly differed between experiments. Specifically, we did not replicate the *n*+2 PoF effect on word *n*. Despite the ample evidence that word *n*+2 was effectively previewed in Experiment 2, *n*+2 preview did not exhibit any immediate effect in pre-boundary fixations on word *n*. The absence of this effect suggests that the same effect in Experiment 1 might have emerged as a statistical artefact reflecting a type-I-error rather than a reliable *n*+2 PoF effect. Alternatively, the diverging results on *n*+2 PoF effects could also be explained with the assumption of word *n*+2 processing difficulties affecting fixation durations with a certain delay. This will be further discussed below.

An additional difference in results between experiments was a weak and non-significant *n*+2 PB effect in Experiment 1 which was significant for young and older readers in Experiment 2. Given its replication in two different samples, this finding appears reliable. Moreover, both experiments consistently revealed significant *n*+2 PB after skipping the previous word *n*+1 and an effect of previewing word *n*+2 if word *n*+1 was fixated. Taken together, the results support the notion that word *n*+2 is parafoveally processed in the *n*+2-boundary paradigm and that its preview information influences the eye-movement system at levels that lead to effects distributed across two or three words in the target region.

Although non-locally distributed preview effects are taken as evidence against a strict confinement to processing only one word at a time (e.g., Kliegl et al., 2006; Wang et al., 2009), some of the present results also seem in disagreement with the notion of parallel word processing. For example, the absence of reliable *n*+2 PoF effects seems to contradict with the parallel activation and processing of several words including word *n*+2. In this case, cross-talk would be expected to affect foveal processing of the pre-boundary word *n*. However, this is not what we found. There was evidence for cross-talk between word *n* processing and the processing difficulty of the upcoming word *n*+1, but no effect for the preview condition of word *n*+2. If it is assumed that processing difficulties of word *n*+2 need more time to accumulate due to greater eccentricity than word *n*+1 (Lee et al., 2003), it could be argued that *n*+2 PoF effects will be delayed relative to any PoF effects from word *n*+1. In this respect, the *n*+2 preview effect on word *n*+1 could represent a delayed PoF effect from word *n*+2 which comes in late prolonging the fixation duration not on the pre-boundary word *n* but on the short post-boundary word *n*+1.

In contrast, the distributed effect pattern is not completely incompatible with SAS models either. PB of word *n*+2 can be obtained if attention is shifted up to word *n*+2 during pre-boundary fixations. As attention can be shifted onto word *n*+2 only if word *n*+1 is completely processed word *n*+1 will cease to be an interesting saccade target and is likely skipped. The *n*+2 PB only after word *n*+1 was skipped is, therefore, in direct support of the SAS assumption. In the present experiment, the *n*+2 PB was also larger if word *n*+1 was a more difficult content word rather than a high-frequent function word. As an early attention shift onto word *n*+2 should be more likely with an easy function word *n*+1 this finding, however, contradicts the SAS prediction.

It must be noted, however, that content words were German nouns and thus distinct from function words by their capitalized initial letter. This may attract early attention shifts to word *n*+1 when such a configurational attractor is encountered in parafoveal vision. However, it should not likewise force a rapid attention shift away from word *n*+1 onto word *n*+2. In other words, it is unlikely that a first rapid attention shift to word *n*+1 would completely overcome further processing disadvantages to such a degree that a rather infrequent content word is processed faster than a high-frequent function word. However, the same interaction was not significant in Experiment 1 although there was a similar trend in target word *n*+2 fixations.

Even more difficult to reconcile with the SAS framework are preview effects prior to the target word, primarily PoF effects but also effects such as the *n*+2 preview effect on word *n*+1 rather than on the target word *n*+2. Restricting processing to one word at a time cross-talk of consecutive word processing is impeded. However, it has been argued that mislocated fixations can “mimic” PoF cross-talk (e.g., Drieghe et al., 2008). Oculomotor error can lead to situations in which attention is already shifted ahead but the saccade intended to synchronize both attention and fixation position falls short leading to a mislocated fixation on the previous word. The duration of such a mislocated fixation – if not immediately corrected – should then reflect processing the attended not the fixated word. Thus, the *n*+2 preview effect on word *n*+1 might indicate an *n*+2 PB effect mislocated on the pretarget word *n*+1 rather than a delayed PoF effect. The nature of this very reliable *n*+2 effect will be further investigated in Chapter 4.

3.4.4 Conclusions

In the present experiment, we could replicate our previous findings of parafoveal processing in the perceptual span extending up to word *n*+2. The results argue against the notion of a strong reduction in the perceptual span with age but provide further evidence that during skilled reading parafoveal information is extracted and utilized even from word *n*+2. At least in an *n*+2-boundary paradigm with a short three-letter word *n*+1, both younger and older adults gained preview from word *n*+2. In contrast to hard-wired physiological constraints in older adults' visual acuity, the present results rather indicate age differences in the degree of resilience as response to distributed processing demand, or in the degree of interference resulting from close parafoveal word *n*+1 neighbors. Both interpretations would be in good agreement with the idea of parallel distributed word processing. Under certain additional assumptions, mislocated fixations might offer an alternative explanation maintaining serial word processing. The recurring issue of whether PoF effects are genuine effects or due to oculomotor error emphasizes the importance of further investigating such alternatives in the *n*+2-boundary paradigm and motivated the following Experiments 3 and 4.

CHAPTER 4
DISSOCIATING DISTRIBUTED SOURCES OF N+2 PREVIEW EFFECTS : EXPERIMENTS 3 AND 4

This chapter has been published in:

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Reading fixations have long been known to reflect processing difficulties associated with the fixated word (Huey, 1908). One critical issue of eye-movement control during reading is whether fixation durations also reflect the processing difficulty of the upcoming, not-yet-fixated words to the right of a fixation. Such PoF effects have elicited a controversial discussion (see 1.2.3). With the present study, we contribute to this debate using a GCDC manipulation in the *n*+2-boundary paradigm crossing the pre- and post-boundary difficulty of word *n*+2. In this paradigm, we can experimentally dissociate the distributed origin of long-range preview effects in fixations after the boundary has been crossed and provide insight into the following questions: Are there genuine PoF effects that can be disentangled from oculomotor error? How do PoF effects evolve for parafoveal words at increasing eccentricities and what is the time course of processing in the perceptual span? Does (correct) preview evoke benefit in later word recognition only, or is there also evidence for (incorrect) preview cost?

4.1 Dissociating the origin of PoF effects

More specifically, the present experiments test one issue that emerged from the previous results of Experiment 1 and 2. One of the most reliable findings in the *n*+2-boundary paradigm so far has been the *n*+2 preview effect on the post-boundary word *n*+1 prior to the target word. This effect can either be interpreted in terms of an *n*+2 PB effect being mislocated on the pretarget word *n*+1, or it could reflect an *n*+2 PoF effect being somehow delayed into word *n*+1fixations. The present manipulation offers an opportunity to test whether this preview effect can be explained by mislocated fixations maintaining a strict serial order of lexical word processing, or if it must be attributed to PoF cross-talk between processing subsequent words in parallel. As a consequence, the dissociation between the two alternatives may also contribute to the more general discussion on the time course of processing inside the perceptual span.

4.1.1 Possible interpretations of direct PoF effects

In light of the diverging and controversial findings with respect to direct PoF effects, demonstrating such effects across different experiments and paradigms may be a first important step. However, their interpretation, even once they are observed, is all but simple because they could emerge for at least three different reasons. First, PoF effects could arise from the predictability of the next word based on prior semantic or syntactic sentence context or from mere transition probabilities (Kliegl et al., 2006). Such an interpretation gets along without the need of assuming any preprocessing of the parafoveal word(s) during a given fixation. Therefore, Kliegl et al. (2006) chose the neutral term successor effect to characterize direct influences of upcoming words on the current fixation duration.

Second, successor effects could indeed reflect the extraction of information of parafoveal words. From this perspective, they have been called PoF effects (Kennedy, 1998; Murray, 1998). Moreover, they have been taken as evidence for parallel distributed processing in the perceptual span. If more than one word is processed during a fixation then parafoveal word properties may also modulate foveal fixation times.

Third, such effects may not be genuine PoF effects but indicate parafoveal information extraction from a mislocated fixation position. For example, due to oculomotor error saccades may undershoot their intended target and land on the word before (McConkie et al., 1988). In such a case, attention may focus the intended saccade target nevertheless, and parafoveal processing difficulty could be reflected in a mislocated fixation on the earlier word (Drieghe et al., 2008). From this perspective, there is no need to assume that more than one word is processed in parallel.

Past research with the boundary paradigm has demonstrated that parafoveal processing during pre-boundary fixations takes place. However, a statistical test to effectively dissociate genuine PoF effects from preprocessing effects in mislocated fixations was usually not an integral part of the experimental design (but see Drieghe et al., 2008). In the following, we introduce a variant of the boundary paradigm that yields statistical tests for both hypotheses in the context of a coherent experimental design. Thus, it provides further insight into whether words in the perceptual span are processed in parallel or in serial fashion.

4.1.2 Dissociating the interpretations in the *n*+2-boundary paradigm

To dissociate genuine PoF effects of parallel word processing from effects in mislocated fixations maintaining serial word processing, we utilized characteristics of the *n*+2-boundary paradigm. As in the previous experiments, the post-boundary word *n*+1 was always three letters long to maximize the likelihood of the subsequent target word *n*+2 to fall inside the perceptual span. As short words tend to be skipped frequently (e.g., Brysbaert & Vitu, 1998; Drieghe et al., 2004), word

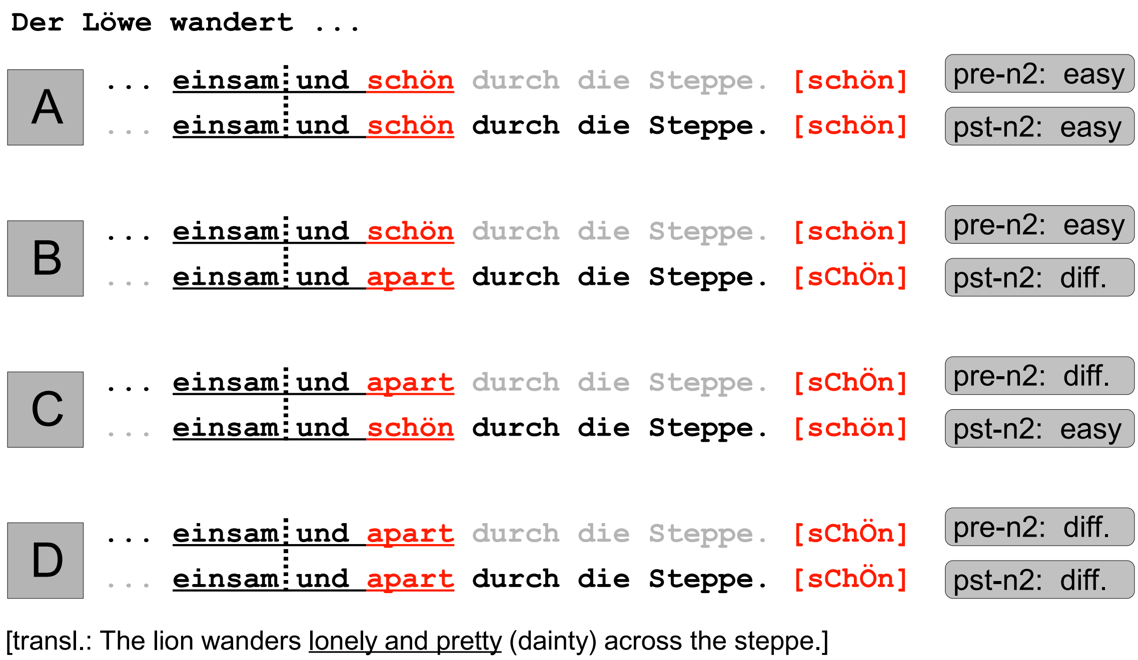

Figure 4.1 Experimental conditions of Experiment 3 and 4. Orthogonally manipulating the *n*+2 pre-boundary (pre-n2) and the *n*+2 post-boundary (pst-n2) difficulty, the four *n*+2 preview conditions are depicted with an example sentence containing a function word *n*+1. High and low frequency words n+2 (Experiment 3) are highlighted in red, in brackets is an example of the orthographic case alternation (Experiment 4). Conditions A and D provide identical preview of word *n*+2, conditions B and C deny identical preview. The target region is underlined, the invisible boundary is represented as a dotted line. An English translation of the example sentence is provided below for the high frequency word *n*+2 (low frequency word *n*+2 in brackets).

n+1 may also be a good candidate for mislocated fixations if skipping of word *n*+1 fails due to oculomotor error. Indeed, Engbert and Krügel (2010) estimated that most fixations on three-letter words are due to failed skipping. In the case of failed skipping, serial word processing predicts the intended saccade target word *n*+2 to be attended and processed (see Kennedy, 2008, for a theoretical distinction of different types of oculomotor error in serial word-processing models).

Most importantly, we orthogonally manipulated the pre- and post-boundary processing difficulty of word *n*+2. The *n*+2 preview difficulty prior to crossing the boundary (i.e., the *n*+2 pre-boundary difficulty) was crossed with the target word *n*+2 difficulty after crossing the boundary (i.e., the *n*+2 post-boundary difficulty). The *n*+2 processing difficulty was operationalized with printed word frequency (Experiment 3) and visual familiarity (i.e., case alternation; Experiment 4). Figure 4.1 illustrates the four primary experimental conditions. For example, word *n*+2 could be previewed as an easy word which was then replaced by a difficult *n*+2 target when the eyes crossed the invisible boundary (Figure 4.1 B). Conversely, word *n*+2 could be presented as a difficult preview during pre-boundary fixations which was then replaced with an easy word *n*+2 target after crossing the boundary (Figure 4.1 C). Both conditions did not allow useful preview of word *n*+2. However, in the two remaining conditions (Figure 4.1 A and D), in which the pre- and post-boundary difficulty of word *n*+2 was identical, preview of word *n*+2 was available.

In previous boundary studies, preview and target word difficulty were either not controlled (e.g., if a phonologically similar preview was used irrespective of its word frequency relative to the target word) or confounded with the preview manipulation (e.g., if a nonword preview with a printed word frequency of zero masked the target word in parafoveal vision). Manipulating the pre- and post-boundary processing difficulty instead allows us to dissociate three theoretically important effects in a single fixation. Moreover, implementing the *n*+2-boundary paradigm, we can trace the time course of these effects across three words in the target region, i.e., word *n*, *n*+1, and *n*+2.

Pre-boundary difficulty. The main effect of *n*+2 pre-boundary difficulty (A+B < C+D; see Figure 4.2, left panel) translates into a PoF effect, irrespective of whether it is measured on word *n*, *n*+1, or *n*+2. If it is measured on the pre-boundary word *n*, it represents the classical PoF effect. If it is measured on word *n*+1, we call it a delayed PoF effect (Kliegl et al., 2007; Risse & Kliegl, 2011). The saccade prior to fixating word *n*+1 triggered the display change of word *n*+2. As word *n*+2 may now be a different word with a different processing demand, finding an effect of the *n*+2 pre-boundary difficulty indicates that preprocessing of the *n*+2 preview is still not terminated although it is not present in parafoveal vision anymore. Theoretically, the main effect of pre-boundary difficulty could also be observed on word *n*+2 which then would indicate a very much delayed PoF effect.

Post-boundary difficulty. The second main effect tests the *n*+2 post-boundary difficulty (A+C < B + D; see Figure 4.2, middle panel). An effect of post-boundary difficulty could occur on word *n*+2 where it would indicate a classical immediacy effect of processing: Easy *n*+2 target words should be fixated shorter than more difficult *n*+2 targets. In principle, we could also observe this effect on word *n*+1. In this case, there are two interpretations. First, it could reflect a direct

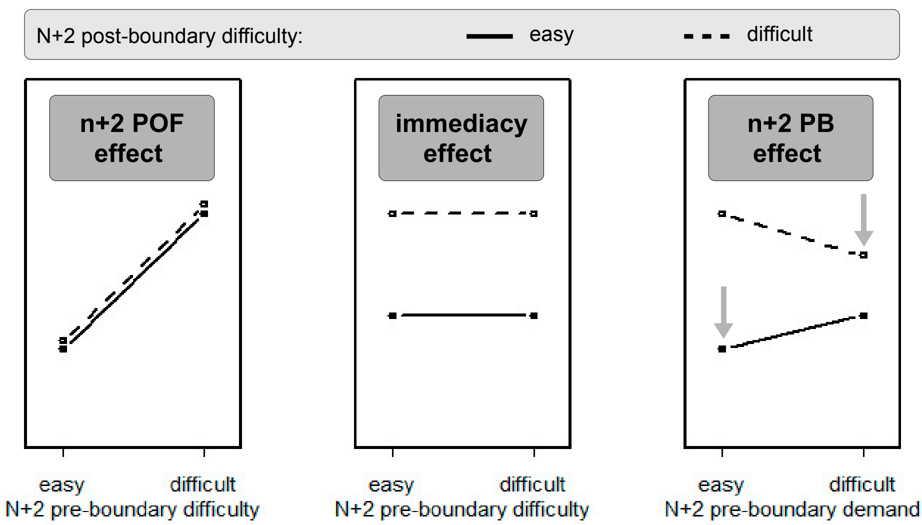

Figure 4.2 Dissociation of *n*+2 processing influences. Illustrated are the three different sources of (pre-)processing that can be dissociated in Experiment 3 and 4: The main effect of *n*+2 pre-boundary difficulty reflecting a POF effect (left panel), an immediacy effect of the *n*+2 post-boundary difficulty (middle panel), and the classical PB effect transalting into an underadditive interaction between *n*+2 pre- and post-boundary difficulty.

PoF effect from word n+2 on word n+1. In contrast to the delayed PoF effect described above, fixation durations on word n+1 should depend on the post-boundary difficulty of word n+2, not its pre-boundary difficulty. Second, it could also represent an immediacy effect of n+2 processing during a mislocated fixation on word n+1 (i.e., a mislocated immediacy effect). If the fixation on word n+1 was intended for word n+2 (i.e., if the fixation represents failed skipping of word n+1), then the effect of n+2 post-boundary difficulty on word n+1 may indicate that attention and therefore processing is focused on the intended saccade target word n+2.

Interaction of pre- and post-boundary difficulty. The unique feature of the present design is that an underadditive interaction of pre- and post-boundary difficulty translates into the PB effect of word n+2 (see Figure 4.2, right panel). Conditions A and D represent identical preview conditions whereas there is a change between n+2 preview and target word in conditions B and C. Thus, if the underadditive interaction of A+D < B+C is statistically significant, we observe an n+2 PB effect with shorter fixation durations after identical preview than after incorrect preview of word n+2. The classical PB is measured on the target word n+2. Again, if skipping of word n+1 fails, a PB in mislocated fixations on word n+1 would be indicative for attention being focused on the intended saccade target word n+2 and thus support the notion of serial word processing. In this case, oculomotor error might be a viable source for distributed processing effects without assuming that word processing is achieved in parallel.

4.1.3 Summary and motivation of Experiment 3 and 4

Manipulating the pre- and post-boundary processing demand of word n+2, we can experimentally dissociate PoF effects, immediacy effects, and PB effects in one common framework. Most indicative are fixation durations after crossing the boundary. During pre-boundary fixations prior to the display change of word n+2 readers are agnostic about the n+2 post-boundary difficulty. However, if the boundary is crossed, we can test the two main effects (i.e., PoF effect and target word n+2 immediacy effect) and the underadditive interaction (i.e., PB effect) with the same statistical power. Using the present 2 x 2 design, the effects map onto three orthogonal contrasts each of which comprises the comparison of two pairs of the four experimental conditions (see above). Thus, in contrast to previous research, we can evaluate how all these effects contribute to the duration of each individual fixation after crossing the boundary instead of comparing effects on the pre-boundary word n with effects on the post-boundary target word.

At the same time, we can dissociate genuine PoF effects from such effects due to oculomotor error. The latter explanation requires that word processing is restricted to the intended saccade target even if oculomotor error leads to a mislocated fixation on an unintended word. If n+1 fixations are often mislocated due to failed skipping of word n+1 then we should expect target word n+2 processing effects on word n+1. Thus, we would predict an immediacy effect of the n+2 post-boundary difficulty and/or a PB effect, but not an effect of the *n*+2 pre-boundary difficulty. The latter finding would disconfirm the mislocated fixation hypothesis and support the notion of genuine PoF effects, although delayed into post-boundary fixations.

As such, the present design allows us to track the time course of parafoveal processing effects across a target region of three words. Novel and crucial is that finding a main effect of the pre-boundary difficulty of word *n*+2 after leaving word *n* would be decisive evidence for parafoveal processing during pre-boundary fixations manifesting itself as a delayed PoF effect. In addition, it can be investigated whether the benefit of previewing word *n*+2 manifests itself even prior to fixating the *n*+2 target. Finding both effects in the same fixation duration after crossing the boundary would suggest not only benefit in later word recognition but also a cost due to preprocessing an incorrect preview.

4.2 Method of Experiment 3 and 4

4.2.1 Participants

In Experiment 3, 60 young adults (11 male, 49 female) participated in a one-hour session. Participants were on average 24 years old (*SD* = 5) and had normal or corrected-to-normal vision. For Experiment 4, data was collected from 32 participants (14 male, 18 female) who were on average 19 years old (*SD* = 2). All participants received either course credit or 7 € for their attendance and had normal or corrected-to-normal vision.

4.2.2 Sentence material

A three-word target region was embedded in simple-structured main clauses without intra-sentential punctuation. For Experiment 3, sentences were constructed according to the material used in Experiment 1 and 2. Due to additional restrictions imposed by manipulating the target word *n*+2 frequency, not all sentence frames could be adopted. The overlap of words in the target region amounted to 87 % for word *n* and 98 % for word *n*+1. Since the frequency of word *n*+2 was explicitly manipulated the overlap with the prior sentence material was with 5 % expectedly low. Word length of the pre-boundary word *n* ranged from 4 to 13 letters (*M* = 7, *SD* = 2). The post-boundary word *n*+1 was always a three-letter word and the target word *n*+2 ranged from four to six letters (*M* = 5, *SD* = 1). Between sentences, the same manipulation of lexical status of word *n*+1 was adopted. Importantly, we manipulated the *n*+2 preview and target word frequency. Each sentence frame enabled both a high-frequent (HF) and a low-frequent (LF) word at position *n*+2 that were matched in word length and fitted into the sentence context. HF words *n*+2 had an average frequency of 307 per million (*SD* = 635) whereas LF words averaged to 3 per million (*SD* = 6). Word *n* frequency amounted to a mean of 306 per million (*SE* = 854), and the short post-boundary word *n*+1 averaged to 2,822 per million (*SE* = 5,235) with content words being of lower frequency (*M* = 33 per million, *SE* = 60) than function words (*M* = 5,611 per million, *SE* = 6,277).

Experiment 4, in contrast, used the identical sentence material as Experiment 1 and 2. Note that no nonword preview condition was implemented in Experiment 4. Instead, pre- and post-boundary processing difficulty of word *n*+2 was manipulated by presenting word *n*+2 either written in lower-case (LC) letters or in alternating case (AC). Since in the German language, the case of the initial letter of a word is a marker for its word class with upper-case word-beginnings indicating a noun, the sequence of alternating cases within a word always started with a lower-case letter followed by an upper-case letter. Thus, there were no differences in word-class information between preview and target word *n*+2 that could be derived from processing the initial letter only.

4.2.3 Apparatus and procedure

Participants were tested with the apparatus described in Experiment 1 (see 2.2.3). Each experiment started with making participants familiar with the apparatus and procedure. Both eyes were calibrated on a standard 9-point grid and re-calibrated every 15 trials. Each trial started with a fixation point on the left side of the horizontal midline that indicated the center of the upcoming sentence-initial word. If gaze detection on the fixation point failed for 2 s, a drift correction was applied in the center of the computer screen. After 2 successive failures a re-calibration was performed. If initial fixation was successful the sentence was displayed on the horizontal midline of the screen. Participants were instructed to read for comprehension. Fixating a dot in the lower right corner signaled the termination of the trial. Comprehension questions were asked after one third of the trials (three-alternative multiple-choice questions).

In each sentence, an invisible boundary was located after word *n* followed by a three-letter content or function word *n*+1. The subsequent word *n*+2 was manipulated contingent on whether the gaze was detected online to be before or after the boundary. In Experiment 3, word *n*+2 was either an HF (e.g., “schön” (transl.: pretty)) or an LF (e.g., “apart” (transl.: dainty)) preview during pre-boundary fixations which was then replaced either by an HF (“schön”) or an LF (“apart”) target word *n*+2 as soon as the eyes crossed the boundary. Each of the 160 test sentences was presented in one of four *n*+2 conditions: (1) HF – HF, (2) HF – LF, (3) LF – HF, or (4) LF – LF. In Experiment 4, word *n*+2 was presented as an LC (e.g., “schön”) or an AC (e.g., “sChÖn”) preview prior to crossing the boundary which was then replaced either by an LC or AC target word *n*+2. Thus again, 160 test sentences were displayed in one of the four *n*+2 conditions: (1) LC – LC, (2) LC – AC, (3) AC – LC, or (4) AC – AC. Apparently, manipulating the *n*+2 pre-and post-boundary difficulty confounded preview of word *n*+2. In conditions 1 and

Pre-bnd. difficulty of word n+2	Post-bnd. difficulty of word n+2	**FW *n*+1**		**CW *n*+1**	
		Skipping word n+1		Skipping word n+1	
		fixated	skipped	fixated	skipped
		M (SD)	*M (SD)*	*M (SD)*	*M (SD)*
Measured on word *n*+2					
easy (HF)	easy (HF)	220 (87)	262 (97)	261 (119)	289 (122)
easy (HF)	difficult (LF)	239 (96)	278 (106)	288 (114)	297 (132)
difficult (LF)	easy (HF)	216 (79)	263 (87)	260 (108)	285 (118)
difficult (LF)	difficult (LF)	238 (101)	282 (106)	283 (112)	302 (131)
Measured on word *n*+1					
easy (HF)	easy (HF)	217 (79)		208 (75)	
easy (HF)	difficult (LF)	211 (76)		213 (85)	
difficult (LF)	easy (HF)	217 (70)		219 (77)	
difficult (LF)	difficult (LF)	216 (78)		212 (75)	
Measured on word *n*					
easy (HF)	easy (HF)	230 (82)	215 (82)	263 (105)	250 (114)
easy (HF)	difficult (LF)	232 (94)	210 (73)	262 (109)	247 (108)
difficult (LF)	easy (HF)	230 (80)	220 (81)	264 (111)	249 (101)
difficult (LF)	difficult (LF)	226 (77)	217 (77)	269 (119)	254 (114)

Table 4.1 Results of Experiment 3. Mean value (*M*) and standard deviation (*SD*) for the entire experimental conditions are summarized based on gaze duration (GD) on the pre-boundary word *n*, the post-boundary word *n*+1, and the target word *n*+2. The results are presented for function word *n*+1 (FW *n*+1) and content word *n*+1 (CW *n*+1) sentences seperately. HF: high frequency word *n*+2. LF: low frequency word *n*+2.

4, in which *n*+2 preview and target word difficulty was identical, word *n*+2 was replaced by itself and participants gained correct preview of word *n*+2 during pre-boundary fixations. In conditions 2 and 3, incorrect preview of word *n*+2 was obtained. Experimental conditions were counterbalanced across participants. After the experiment, participants were asked whether they noticed any display changes.

4.2.4 Data analysis

LMMs were conducted on log-transformed fixation durations. As fixed effects, we specified the *n*+2 pre-boundary difficulty (easy: HF/LC vs. difficult: LF/AC) and the *n*+2 post-boundary difficulty (easy: HF/LC vs. difficult: LF/AC) and the lexical status of word *n*+1 (function vs. content word); factors were effect-coded and centred around zero using contrast coefficients of -0.5 and 0.5. Skipping of word *n*+1 (fixated vs. skipped) was further considered as post-hoc predictor. During pre-boundary fixations on word *n*, participants are oblivious to the post-boundary difficulty of word *n*+2 and this predictor should not play a role in explaining variance of word *n* fixation durations. As a matter of fact, excluding *n*+2 post-boundary difficulty from the respective LMM did not impair the model fit for word *n*. Therefore, we pooled the data across this variable for the analysis of pre-boundary fixations on word *n*. Participants, the unique word index, and sentence number (items) were submitted as random effects.

4.3 Results of Experiment 3

In Experiment 3, the frequency of the *n*+2 preview and target word was manipulated to control the pre-and post-boundary processing difficulty of word *n*+2. Word *n*+2 was presented either as a high frequency word (HF; easy) or as a low frequency word (LF; difficult). No participant reported to have noticed any display changes. Therefore, data of all 60 subjects was analyzed after removing 6 % of a total of 9,600 sentences due to blinks and signal losses. Further sentences were excluded if the fixation onset after crossing the boundary preceded the termination of the display change, amounting to additional 14 % of data loss. Fixations with durations shorter than 50 ms and longer than 750 ms, being the first or last fixation within the sentence, or when both eyes did not fixate the same word were also removed (for a more detailed description see 2.2.4). In total, 30 % of the recorded word-based fixations in the target region were excluded (21 % for word *n*, 42 % for word *n*+1, 29 % for word *n*+2). This left 6,827 valid GDs on word *n*, 3,512 on word *n*+1, and 6,977 on word *n*+2. Summary statistics for GDs are provided in Table 4.1.

4.3.1 Target word *n*+2

N+2 immediacy effect. Fixation durations on word *n*+2 showed a strong immediacy effect of the *n*+2 post-boundary difficulty (GD: b = .07, SE = .01, t = 6.29; FFD: b = .05, SE = .01, t = 4.78; SFD: b = .06, SE = .01, t = 5.00). N+2 GDs were 19 ms longer (FFD: 12 ms, SFD: 14 ms) on

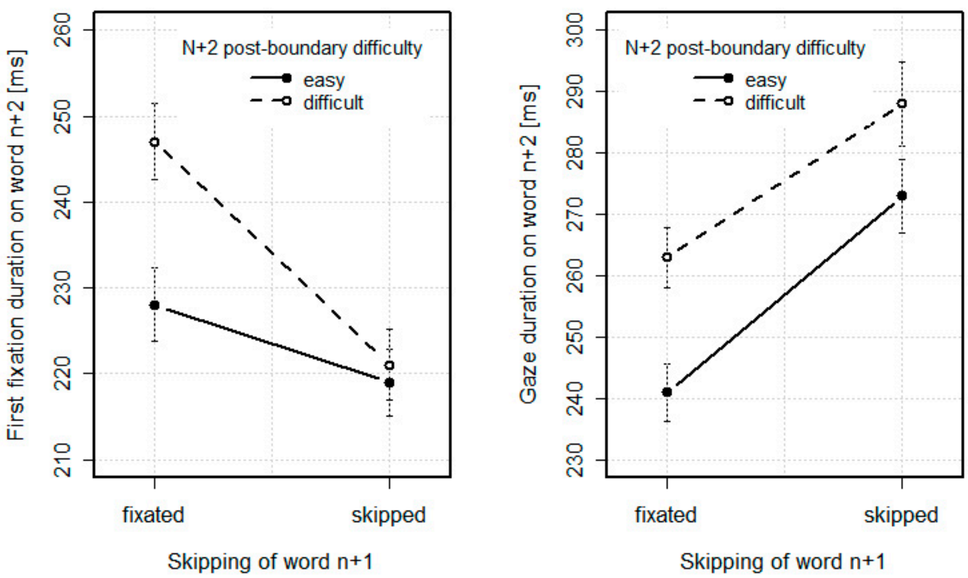

Figure 4.3 Immediacy effect of *n*+2 post-boundary processing. Mean target word *n*+2 fixation durations are depicted depending on the *n*+2 post-boundary difficulty and skipping of the previous word *n*+1. FFDs on the *n*+2 target word (left panel) are contrasted with the *n*+2 GDs (right panel).

a difficult *n*+2 target (i.e., LF word *n*+2) than on an easy *n*+2 target (i.e., HF word *n*+2). The immediacy effect of *n*+2 post-boundary difficulty was more pronounced if the previous word *n*+1 had been fixated than if it was skipped (interaction of *n*+2 post-boundary difficulty and *n*+1 skipping; GD: 22 ms vs. 15 ms, $b = -.06$, $SE = .02$, $t = -3.26$; FFD: 19 ms vs. 2 ms, $b = -.07$, $SE = .02$, $t = -4.62$; SFD: 20 ms vs. 4 ms, $b = -.07$, $SE = .02$, $t = -4.11$). Target word FFDs (Figure 4.3, left panel) showed a disadvantage for processing a difficult *n*+2 target if the previous word *n*+1 was fixated (similar results for SFDs). This is counterintuitive because fixating word *n*+1 should allow additional preview of word *n*+2 and reduce its processing demand if it is then fixated. In contrast, GDs on word *n*+2 (Figure 4.3, right panel) rather suggested a disproportionate benefit for an easy word *n*+2 target if it was additionally previewed fixating word *n*+1. There was no evidence for an interaction with the lexical status of word *n*+1 (all absolute *t* values < .90). The 3-way interaction was also not significant (all absolute *t* values < 1.35).

Delayed n+2 PoF effect. There was no effect of the *n*+2 pre-boundary difficulty in fixation durations on the target word *n*+2 (GD: $b = .004$, $SE = .01$, $t = .43$; FFD: $b = .002$, $SE = .01$, $t = .25$; SFD: $b = .003$, $SE = .01$, $t = .28$). The interactions with the lexical status or skipping of word *n*+1 were also not significant (GD: all absolute *t* values < 1.64; FFD: all absolute *t* values < 1.19; SFD: all absolute *t* values < 1.48). However, foreshadowing a significant effect of the *n*+2 pre-boundary difficulty in Experiment 4, we ran separate LMM's for *n*+2 fixation durations after fixating and skipping word *n*+1. If word *n*+1 was fixated, the *n*+2 pre-boundary difficulty was clearly not significant (GD: $b = -.04$, $SE = .01$, $t = -.65$; FFD: $b = -.01$, $SE = .01$, $t = -.75$; SFD:

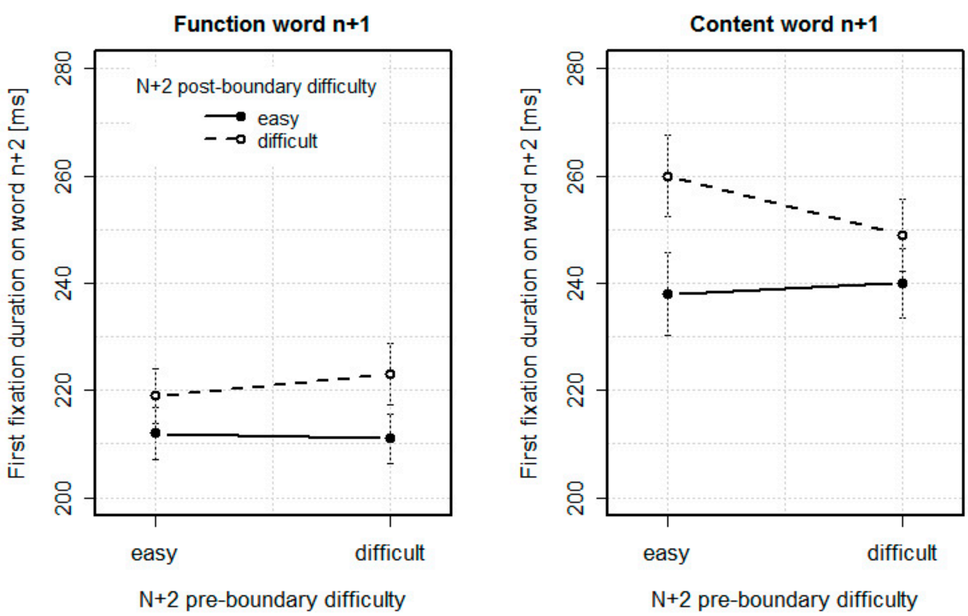

Figure 4.4 Preview benefit on word *n*+2. The interaction of *n*+2 pre- and post-boundary difficulty is shown with respect to the lexical status of the preceding word *n*+1. Mean target word *n*+2 FFDs are presented separately after function words (left panel) an after content words *n*+1 (right panel).

b = -.01, *SE* = .01, *t* = -.99). The effect increased slightly if word *n*+1 was skipped, but this was also not significant (GD: *b* = .02, *SE* = .01, *t* = 1.69; FFD: *b* = .01, *SE* = .01, *t* = 1.17; SFD: *b* = .01, *SE* = .01, *t* = 1.07).

N+2 PB effect. The theoretically important interaction between *n*+2 pre- and post-boundary difficulty displaying the PB effect on the target word *n*+2 was not significant (GD: *b* = .003, *SE* = .02, *t* = .19; FFD: *b* = -.01, *SE* = .02, *t* = -.44; SFD: *b* = -.01, *SE* = .02, *t* = -.62). The PB was not modulated by skipping word *n*+1 (GD: *b* = .03, *SE* = .03, *t* = .74; FFD: *b* = .01, *SE* = .03, *t* = .21; SFD: *b* = -.01, *SE* = .04, *t* = -.16). However, as Figure 4.4 illustrates, there was some evidence for a PB effect on word *n*+2 in FFDs if word *n*+1 was the more difficult content word (3-way interaction of *n*+1 lexical status and *n*+2 pre- and post-boundary difficulty: *b* = -.06, *SE* = .03, *t* = -1.97). The interaction was not significant in GDs (*b* = -.02, *SE* = .03, *t* = -.64) or SFDs (*b* = -.03, *SE* = .04, *t* = -.83). The interaction including all variables was also not significant (with all absolute *t* values < .64).

N+1 spillover effects. There was a substantial cost of skipping word *n*+1 in word *n*+2 GDs (*b* = .27, *SE* = .01, *t* = 26.29) and SFDs (*b* = .10, *SE* = .01, *t* = 8.63), but not in FFDs (*b* = .01, *SE* = .01, *t* =.93). In addition, fixation durations on word *n*+2 were longer if the preceding word *n*+1 was a content rather than a function word (GD: *b* = .13, *SE* = .02, *t* = 6.86; FFD: *b* = .09, *SE* = .04, *t* = 6.36; SFD: *b* = .10, *SE* = .02, *t* = 5.66). This spillover effect was larger if word *n*+1 was fixated than if it was skipped (GD: *b* = -.12, *SE* = .02, *t* = -6.60; FFD: *b* = -.21, *SE* = .02, *t* = -12.4; SFD: *b* = -.21, *SE* = .02, *t* = -11.4). However, the pattern differed between FFDs (similar to SFDs) and GDs. While for FFDs it seemed that the spillover effect of the processing difficulty of word *n*+1 was absent after skipping it, GDs suggested a general spillover for content words *n*+1 independent of skipping but with disproportionately shorter *n*+2 GDs if a function word *n*+1 was fixated. No other effects reached significance (with all absolute *t* values < 1.35).

4.3.2 Post-boundary word *n*+1

Delayed n+2 PoF effect. If the critical word *n*+1 was not skipped, there was only one significant effect: Fixation durations on word *n*+1 were modulated by the *n*+2 pre-boundary difficulty (GD: *b* = .02, *SE* = .01, *t* = 2.15; FFD: *b* = .02, *SE* = .01, *t* = 2.18; SFD: *b* = .02, *SE* = .01, *t* = 2.25). This effect was quite small with only 4 ms longer GDs if word *n*+2 had been previewed as an LF word rather than an HF word (*n*+2 pre-boundary difficulty effect for FFDs: 3 ms; SFD: 4 ms). The lexical status of word *n*+1 did not significantly interact with the *n*+2 pre-boundary difficulty (all absolute *t* values < .98). Given that we obtained evidence for *n*+2 PB only after content words, we ran additional LMM's for fixations on function and content words separately. For

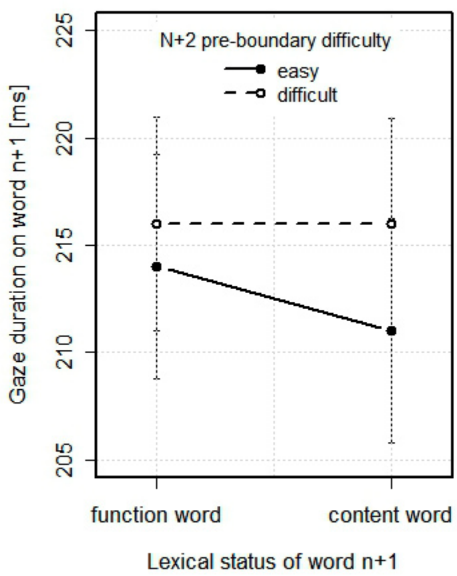

Figure 4.5 Delayed *n*+2 parafoveal-on-foveal effect on the post-boundary word *n*+1. Plotted are the mean GDs on function or content words *n*+1 conditional on the pre-boundary difficulty of word *n*+2.

fixation durations on function words *n*+1, there was no effect of the *n*+2 pre-boundary difficulty in any fixation duration measure (all t values < 1.16). Depicted in Figure 4.5, the delayed *n*+2 PoF effect was significant only in fixation durations on content words (GD: 4 ms, $b = .03$, $SE = .01$, $t = 2.36$; FFD: 5 ms, $b = .03$, $SE = .01$, $t = 2.18$; SFD: 4 ms, $b = .03$, $SE = .01$, $t = 2.34$).

Mislocated n+2 immediacy and PB effect. The mislocated immediacy effect of the *n*+2 post-boundary difficulty – previewed from a neighboring n-1-position during fixating word *n*+1 – was not significant in any of the fixation duration measures (all absolute t values > .73). In addition, there was no evidence for an *n*+2 PB effect mislocated on word *n*+1 (interaction of *n*+2 pre- and post-boundary difficulty: all t values < .96). No other interaction involving the *n*+2 post-boundary difficulty was significant (all absolute t values < 1.63).

Immediacy effect of n+1 lexical status. The lexical status of word *n*+1 did not elicit an immediacy effect in fixation durations on word *n*+1 (all absolute t values < .37). In fact, this could be taken as evidence for oculomotor error as the main source of *n*+1 fixations making further current word processing dispensable.

4.3.3 Pre-boundary word *n*

N+2 PoF effect. GDs on word *n* showed a marginal effect of the *n*+2 pre-boundary difficulty ($b = .01$, $SE = .01$, $t = 1.98$). However, GDs were on average only 2 ms longer if word *n*+2 was presented as an LF preview relative to an HF preview. Moreover, this *n*+2 PoF effect was not significant in FFDs ($b = .01$, $SE = .01$, $t = 1.10$) or SFDs ($b = .01$, $SE = .01$, $t = 1.52$). As illustrated in Figure 4.6, word *n* GDs showed a trend towards an increased *n*+2 PoF effect prior to

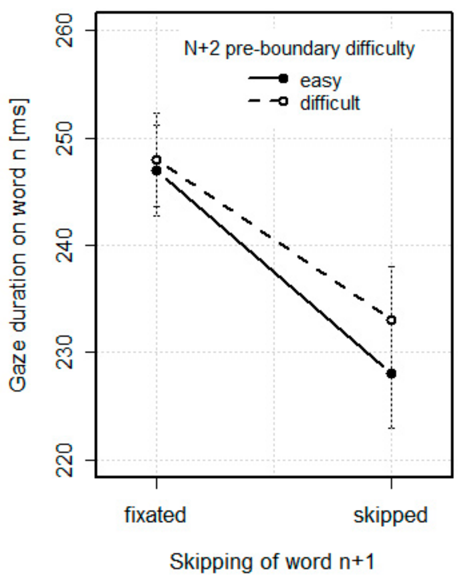

Figure 4.6 N+2 parafoveal-on-foveal effect on the pre-boundary word *n*. Plotted are the mean word *n* GDs conditional on the pre-boundary difficulty of word *n*+2 prior to fixating or skipping the upcoming word *n*+1.

skipping word *n*+1 (GD: *b* = .03, *SE* = .02, *t* = 1.76; FFD: *b* = .02, *SE* = .01, *t* = 1.40; SFD: *b* = .02, *SE* = .01, *t* = 1.34). Separate LMM's for word *n* fixations if word *n*+1 was skipped confirmed a 5 ms PoF effect of word *n*+2 in GDs (*b* = .03, *SE* = .01, *t* = 2.43), which was weaker in FFDs (*b* = .02, *SE* = .01, *t* = 1.88) and in SFDs (*b* = .02, *SE* = .01, *t* = 1.93). The *n*+2 PoF effect was absent if word *n*+1 was fixated (all absolute *t* values < .28). The *n*+2 pre-boundary difficulty did not interact with the lexical status of the upcoming *n*+1 (all absolute *t* values < 1.01). The 3-way interaction was also not significant (all absolute *t* values < .44).

N+1 PoF effect. Word *n* fixation durations were longer if the upcoming word *n*+1 was a more difficult content rather than an easy function word (GD: 36 ms, *b* = .14, *SE* = .02, *t* = 5.69; FFD: 8 ms, *b* = .03, *SE* = .02, *t* = 2.00; SFD: 10 ms, *b* = .05, *SE* = .02, *t* = 2.93). This PoF effect of the neighboring word *n*+1 interacted with skipping of word *n*+1, but only in GDs (*b* = .05, *SE* = .02, *t* = 3.03), not in FFDs (*b* = .02, *SE* = .01, *t* = 1.40) or SFDs (*b* = .02, *SE* = .01, *t* = 1.44). The main effect of *n*+1 skipping contributing to the interaction was also significant (GD: *b* = .02, *SE* = .01, *t* = 2.34; FFD: *b* = -.05, *SE* = .01, *t* = -6.10; SFD: *b* = -.03, *SE* = .01, *t* = -4.03). The estimated slope for the *n*+1 skipping effect was positive for GDs indicating a cost prior to skipping word *n*+1. In contrast, results in Table 4.1 suggest that GDs prior to skipping word *n*+1 were 18 ms shorter than prior to fixating word *n*+1. If GDs were residualized for random intercepts (i.e., participants, words, and items), the mean skipping effect was, however, slightly positive with 5 ms longer fixation durations prior to skipping word *n*+1 confirming the results from the LMM. For FFDs and SFDs, the skipping benefit (i.e., negative slope in the LMM) amounted to 16 ms and 15 ms, respectively.

4.3.4 Summary of results of Experiment 3

The results of Experiment 3 confirm that it is possible to investigate both PB and PoF effects in one single approach if the pre- and post-boundary difficulty of word *n*+2 is manipulated gaze-contingently instead of preview of word *n*+2 only. Moreover, we could track such preview effects across the three words in the target region which allows us conclusions about their time course.

With all caution necessary due to the very small effect sizes, word *n* fixation durations showed some modulation due to the *n*+2 pre-boundary difficulty, mainly if word *n*+1 was afterwards skipped. In addition to this weak *n*+2 PoF effect, there was a substantial PoF effect of the upcoming word *n*+1. Taken together, this can be counted as evidence for direct effects of preprocessing the parafoveal word *n*+1, maybe even word *n*+2.

Results on word *n*+1 present a clearer picture: In the absence of significant immediate processing effects of the currently fixated word *n*+1, fixation durations were modulated by the *n*+2 pre-boundary processing demand only. There was no evidence for a PB effect in mislocated fixations on word *n*+1. The effect of the *n*+2 preview difficulty in post-boundary fixation durations strongly suggests a delayed PoF effect. Thus, oculomotor error seems not sufficient to explain distributed processing effects such as the delayed PoF effect on word *n*+1. The results rather suggest that words are processed in parallel during pre-boundary fixations, but that due to weaker signals of a more eccentric word *n*+2 the preview difficulty influences saccade timing with a certain delay.

In the presence of a 19-ms-immediacy effect of the *n*+2 post-boundary difficulty we did not find strong evidence for additional processing benefits on the target word *n*+2 if correct preview was available. However, PB was obtained in FFDs after content words suggesting that at least in some conditions *n*+2 preview information was effectively used in later target word processing. It should be noted that the only evidence for an *n*+2 PB effect was constrained to sentences with a more difficult word *n*+1, contrary to what is expected if attention is shifted serially to word *n*+2 conditional on complete lexical processing of word *n*+1.

However, the observed *n*+2 effects were generally small, even smaller than in the previous experiments. This shortcoming could be due to the fact that we manipulated a high-level linguistic property of word *n*+2 (i.e., word frequency) to impose different *n*+2 processing demands prior to and after crossing the boundary. During pre-boundary fixations, word *n*+2 must have been preprocessed up to a lexical level to reveal effects in the present experiment. In Experiment 4 we therefore replicated the experiment using an orthographic difficulty manipulation for word *n*+2.

4.4 Results of Experiment 4

In Experiment 4, the visual familiarity of word *n*+2 was manipulated in order to vary the *n*+2 pre- and post-boundary difficulty. Therefore, word *n*+2 was presented either in familiar lower-case

		FW *n*+1		CW *n*+1	
		Skipping word *n*+1		Skipping word *n*+1	
Pre-bnd. difficulty of word *n*+2	Post-bnd. difficulty of word *n*+2	fixated *M (SD)*	skipped *M (SD)*	fixated *M (SD)*	skipped *M (SD)*
Measured on word *n*+2					
easy (LC)	easy (LC)	205 (82)	235 (80)	238 (113)	235 (84)
easy (LC)	diffic. (AC)	234 (88)	296 (102)	275 (110)	301 (119)
diffic. (AC)	easy (LC)	199 (76)	242 (79)	225 (101)	251 (97)
diffic. (AC)	diffic. (AC)	236 (94)	280 (100)	265 (121)	260 (110)
Measured on word *n*+1					
easy (LC)	easy (LC)	205 (82)		198 (66)	
easy (LC)	diffic. (AC)	192 (55)		206 (77)	
diffic. (AC)	easy (LC)	218 (67)		233 (85)	
diffic. (AC)	diffic. (AC)	208 (70)		224 (80)	
Measured on word *n*					
easy (LC)	easy (LC)	235 (81)	222 (87)	270 (116)	231 (85)
easy (LC)	diffic. (AC)	229 (95)	222 (84)	266 (106)	254 (116)
diffic. (AC)	easy (LC)	223 (75)	216 (82)	259 (100)	246 (94)
diffic. (AC)	diffic. (AC)	221 (73)	222 (81)	255 (98)	227 (81)

Table 4.2 Results of Experiment 4. Mean value (*M*) and standard deviation (*SD*) for the entire experimental conditions are summarized based on gaze duration (GD) on the pre-boundary word *n*, the post-boundary word *n*+1, and the target word *n*+2. The results are presented for function word *n*+1 (FW *n*+1) and content word *n*+1 (CW *n*+1) sentences seperately. LC: lower-case word *n*+2. AC: alternating-case word *n*+2.

notation (LC; easy) or in unfamiliar alternating-case letters (AC; difficult). On the lexical level, *n*+2 preview and target were always identical. Moreover, the orthographic *n*+2 manipulation implied that participants fixated an AC target in conditions in which the post-boundary processing demand of word *n*+2 was difficult.

Data of 10 participant were excluded who had noticed some display changes. For the remaining 22 participants, blinks and signal losses disabled 6 % of 3,520 possible sentences. Additional 4 % of sentences were excluded because the display change was not completed prior to fixation onset after crossing the boundary. Individual fixations were removed if they were shorter than 50 ms or longer than 750 ms, if they were the first or last fixation within the sentence, or when both eyes did not fixate the same word. In total, about 9 % of the recorded word-based fixations in the target region were excluded leaving 3,221 valid GD on word *n*, 1,470 on word *n*+1, and 2,796 on word *n*+2 for analysis. The results of the experimental conditions are summarized in Table 4.2.

4.4.1 Target word *n*+2

N+2 immediacy effect. The *n*+2 post-boundary difficulty elicited a strong immediacy effect in

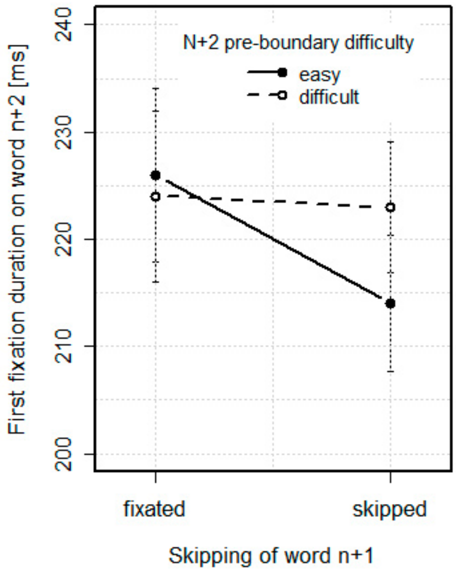

Figure 4.7 Delayed parafoveal-on-foveal effect on the target word *n*+2. Plotted are the mean FFDs conditional on fixating or skipping the preceding word *n*+1 and the *n*+2 pre-boundary difficulty.

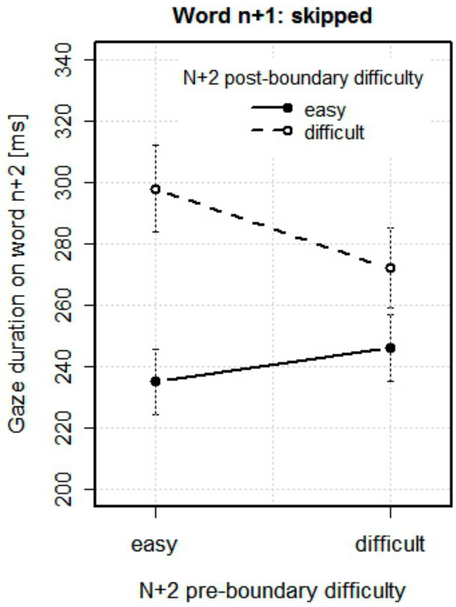

Figure 4.8 Preview benefit effect on the target word *n*+2. Plotted are the mean GDs after skipping word *n*+1 conditional on the pre-and post-boundary difficulty of word *n*+2.

fixation durations on word *n*+2. GDs were 40 ms longer if word *n*+2 was fixated as the more difficult AC target than if it was presented in LC letters (b = .15, SE = .02, t = 11.3; FFD: 24 ms, b = .10, SE = .01, t = 7.12; SFD: 29 ms, b = .12, SE = .02, t = 8.40). Skipping word *n*+1 modulated the immediacy effect of *n*+2 post-boundary difficulty (SFD: b = -.07, SE = .03, t = -2.50; FFD: b = -.10, SE = .03 t = -3.45; but not GD: b = -.02, SE = .03, t = -.64). Similar to Experiment 3, skipping word *n*+1 reduced the effect of *n*+2 post-boundary difficulty in FFDs from 32 ms if word *n*+1 was fixated to 15 ms if word *n*+1 was skipped (SFD: 32 ms vs. 25 ms; GD: 36 ms vs. 44 ms). Again, this is counter to the notion of gaining additional preview of word *n*+2 on the previous fixation on word *n*+1. N+2 post-boundary difficulty did not interact with the lexical status of the previous word *n*+1 (GD: b = -.04, SE = .03, t = -1.35; FFD: b = -.03, SE = .03, t = -1.17; SFD: b = -.05, SE = .03, t = -1.55). The 3-way interaction was also not significant (all absolute t values < 1.65).

Delayed n+2 PoF effect. N+2 pre-boundary difficulty had no effect on target word fixation durations (GD: b = -.01, SE = .01, t = -.97; FFD: b = .02, SE = .01, t = 1.19; SFD: b = -.003, SE = .02, t = -.22). Only if word *n*+1 was skipped, there was significant spillover of the *n*+2 pre-boundary difficulty in FFDs on word *n*+2 (interaction of *n*+2 pre-boundary difficulty and *n*+1 skipping: b = .06, SE = .03, t = 2.24). As Figure 4.7 illustrates, FFDs after skipping word *n*+1 were 9 ms longer if word *n*+2 was presented as a difficult AC preview prior to crossing the boundary. The SFD pattern was similar but attenuated and thus not significant (b = .04, SE =

.03, t = 1.45). If word n+1 was skipped, word n+2 FFDs and SFDs reflected the first fixation after crossing the boundary. In contrast, GDs also included refixations of the target word n+2 and immediacy effects might superimpose pre-boundary spillover. In fact, the interaction of n+1 skipping and n+2 pre-boundary difficulty in GDs was far from significance (b = .02, SE = .03, t = .78). The lexical status of word n+1 did not modulate the effect of n+2 pre-boundary difficulty (all absolute t values < .96). The 3-way interaction was not significant either (all absolute t values < .44).

N+2 PB effect. There was also evidence for a PB effect on the target word n+2. Depicted in Figure 4.8, after skipping word n+1, GDs on word n+2 revealed an underadditive interaction between the n+2 pre- and post-boundary difficulty (3-way interaction: b = -.15, SE = .06, t = -2.60). In SFDs, there was a similar trend (b = -.11, SE = .06, t = -1.77), but not in FFDs (b = -.05, SE = .06, t = -.82). The associated 2-way interaction was only weak in GDs (n+2 pre- and post-boundary difficulty: b = -.05, SE = .03, t = -1.79) and not significant in FFDs (b = .01, SE = .03, t = .48) and SFDs (b = -.03, SE = .03, t = -.94). In contrast to Experiment 3, there was no evidence for a stronger PB effect after content words n+1 (3-way interaction n+2 pre- and post-boundary difficulty and n+1 lexical status, GD: b = -.07, SE = .06, t = -1.11; FFD: b = -.04, SE = .06, t = -.65; SFD: b = -.10, SE = .06, t = -1.66). All variance was mainly captured by skipping word n+1.

N+1 spillover effects. Skipping the previous word n+1 resulted in costs on the target word, significant in GDs (b = .23, SE = .02, t = 12.9) and SFDs (b = .08, SE = .02, t = 4.41) but not in FFDs (b = .02, SE = .02, t = 1.15). The lexical status of word n+1 elicited a strong spillover effect in fixation durations on word n+2 with longer fixation durations after a more difficult content word (GD: b = .06, SE = .03, t = 3.00; FFD: b = .04, SE = .02, t = 2.23; SFD: b = .04, SE = .02, t = 2.16). Moreover, the n+1 spillover on word n+2 was restricted to fixating word n+1 and was absent if word n+1 was skipped (interaction of n+1 skipping and n+1 lexical status, GD: b = -.11, SE = .03, t = -3.70; FFD: b = -.15, SE = .03, t = -5.50; SFD: b = -.14, SE = .03, t = -4.61).

4.4.2 Post-boundary word *n*+1

Delayed n+2 PoF effect. Fixation durations on word n+1 revealed an effect of the n+2 pre-boundary difficulty with 22 ms longer GDs if word n+2 was a difficult AC preview prior to the current fixation (b = .10, SE = .02, t = 5.52; FFD: 21 ms, b = .10, SE = .02, t = 5.32; SFD: 21 ms, b = .10, SE = .02, t = 5.37). N+2 pre-boundary difficulty did not interact with the lexical status of the currently fixated word n+1 (all absolute t values < .98). However, separate LMM's

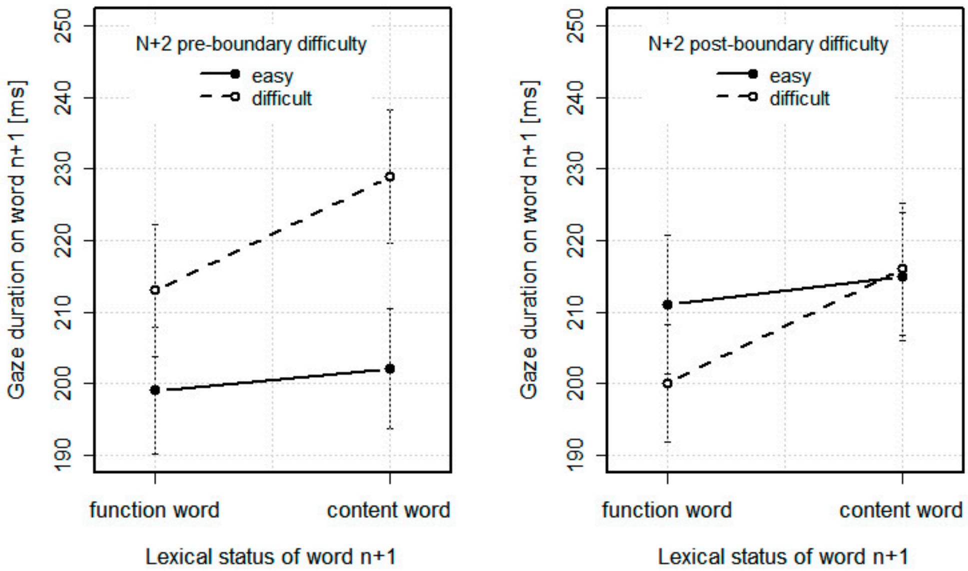

Figure 4.9 Delayed parafoveal-on-foveal effect and magnetic effect of attraction. Plotted are the mean GDs on the post-boundary word *n*+1 conditional on the lexical status of word *n*+1. The left panel depicts the effect of the pre-boundary difficulty of word *n*+2, the right panel shows the *n*+2 post-boundary difficulty effect prior to the target.

for *n*+1 fixations on function and content words suggested that the *n*+2 pre-boundary spillover was more pronounced on content words (Figure 4.9, left panel, GD: 27 ms, *b* = .12, *SE* = .03, *t* = 4.56; FFD: 25 ms, *b* = .11, *SE* = .03, *t* = 4.28; SFD: 26 ms, *b* = .11, *SE* = .03, *t* = 4.35) than on function words (GD: 14 ms, *b* = .09, *SE* = .02, *t* = 3.55; FFD: 14 ms, *b* = .09, *SE* = .02, *t* = 3.55; SFD: 14 ms, *b* = .09, *SE* = .02, *t* = 3.55).

Mislocated n+2 immediacy and PB effect. N+1 fixation durations showed no evidence for a PB effect of word *n*+2 mislocated on word *n*+1 (interaction *n*+2 pre- and post-boundary difficulty: all absolute *t* values < .51; 3-way interaction with *n*+1 lexical status: all absolute *t* values < .38). In addition, there was a tendency towards shorter *n*+1 fixations if the post-boundary difficulty of the neighboring *n*+2 target was high (i.e., an AC target, GD: -4 ms, *b* = -.03, *SE* = .02, *t* = -1.83; FFD: -5 ms, *b* = -.03, *SE* = .02, *t* = -1.82; SFD: -4 ms, *b* = -.03, *SE* = .02, *t* = -1.80). The negative effect of the neighboring word *n*+2 post-boundary difficulty, similar to a magnetic effect of attraction, was only present if a function word was fixated (Figure 4.9, right panel, GD: -11 ms, *b* = -.06, *SE* = .02, *t* = -2.39; FFD: -11 ms, *b* = -.06, *SE* = .02, *t* = -2.39; SFD: -11 ms, *b* = -.06, *SE* = .02, *t* = -2.39) and not significant on content words (GD: *b* = -.01, *SE* = .03, *t* = -.37; FFD: *b* = -.01, *SE* = .03, *t* = -.35; SFD: *b* = -.01, *SE* = .03, *t* = -.31).

Immediacy effect of n+1 lexical status. Again, the lexical status of the currently fixated word *n*+1 had no immediate effect on GDs (*b* = .02, *SE* = .03, *t* = .62), FFDs (*b* = .01, *SE* = .03, *t* = .46), or SFDs (b = .01, SE = .03, t = .50). This supports the conclusion from Experiment 3 that not much current word processing was rendered during fixating word n+1 and that a high proportion of these fixations might be failed skippings due to oculomotor error.

4.4.3 Pre-boundary word *n*

N+2 PoF effect. N+2 pre-boundary difficulty was not significant in word n fixation durations, neither in GDs (b = -.02, SE = .01, t = -1.67), nor in FFDs (b = -.01, SE = .01, t = -1.09), or SFD s (b = -.02, SE = .01, t = -1.58). It did not interact with skipping the upcoming word n+1 or with the lexical status of word n+1 (all absolute t values < .59).

N+1 PoF effect. Fixation durations on the pre-boundary word n showed a substantial PoF effect of the neighboring word n+1 (GD: b = .12, SE = .02, t = 5.30; FFD: b = .04, SE = .02, t = 2.48; SFD: b = .06, SE = .02, t = 3.10). GDs on word n were 29 ms if longer the upcoming word n+1 was a content word rather than a function word (FFD: 9 ms; SFD: 11 ms). The interaction with skipping word n+1 was not significant (all absolute t values < .20). There was an additional effect of skipping word n+1 in word n GDs (b = .04, SE = .02, t = 2.71) and in FFDs (b = -.03, SE = .01, t = -2.17) but not in SFDs (b = -.02, SE = .01, t = -1.33). Similar to Experiment 3, the skipping main effect was estimated as a positive predictor for GDs, while the mean GDs in Table 4.2 suggested 18 ms skipping benefit. Again, if GDs were residualized for random intercepts (i.e., participants, words, and items), the mean skipping effect turned positive (8 ms cost) and confirmed the outcome from the LMM. FFDs and SFDs showed consistent 12 ms and 14 ms skipping benefits, respectively.

4.4.4 Summary of results of Experiment 4

Experiment 4 mainly replicated the effects from Experiment 3. During fixations on the pre-boundary word n the parafoveal words n+1 and n+2 are supposed to be preprocessed. We found again a substantial PoF effect of the neighboring word n+1, but no such evidence for previewing word n+2. However, replicating the delayed PoF effect of word n+2 on the next word n+1 indicated that the n+2 preview was, nevertheless, succesfully preprocessed during pre-boundary fixations. Moreover, the delayed PoF effect amounted to 22 ms in Experiment 4 compared to a 4 ms effect in Experiment 3. Again, there was no evidence for a mislocated PB on word n+1 if identical preview of word n+2 was available. While the immediacy effect of the n+2 post-boundary difficulty on word n+2 was clearly positive, word n+1 revealed a tendency towards a negative effect of the n+2 post-boundary difficulty. Given that word n+1 fixations are mostly mislocated, the results are contrary to the assumption that during mislocated fixations processing is limited to the intended saccade target (i.e., word n+2) only.

As in Experiment 3, the PB effect manifested itself not before word n+2 was fixated. It was pronounced if the previous word n+1 was skipped. In addition, we obtained an effect of the n+2 pre-boundary difficulty in n+2 FFDs if word n+1 was skipped. As this is the first fixation after crossing the boundary, the result is consistent with a delayed PoF effect which is obtained on word n+1 if it is fixated or on word n+2 if word n+1 is skipped. Therefore, in Experiment 4 we basically replicated the time course of preview effects across word n, n+1, and n+2 suggested by Experiment 3. Moreover, we also dissociated three different sources of processing in fixation durations on a single word. Fixation durations on word n+2 reflected an immediacy effect of processing, a PB due to information integration across saccades, and a delayed PoF effect of the n+2 preview difficulty if the first post-boundary saccade lands directly on word n+2 skipping word n+1.

4.5 Discussion of Experiment 3 and 4

In the present study, we proposed an experimental design that eliminates the confound of preview difficulty with preview condition in the boundary paradigm. Manipulating the pre- and post-boundary difficulty of word n+2, three independent sources of processing could be tested and dissociated in individual fixation durations after crossing the boundary: (1) The immediacy effect of processing the n+2 target word (i.e., n+2 post-boundary difficulty), (2) a delayed PoF effect of preprocessing the n+2 preview during pre-boundary fixations (i.e., n+2 pre-boundary difficulty), and (3) PB as a consequence of integrating parafoveally extracted information across saccades (i.e., interaction of n+2 pre- and post-boundary difficulty).

Using a frequency (Experiment 3) and an orthographic (Experiment 4) difficulty manipu-

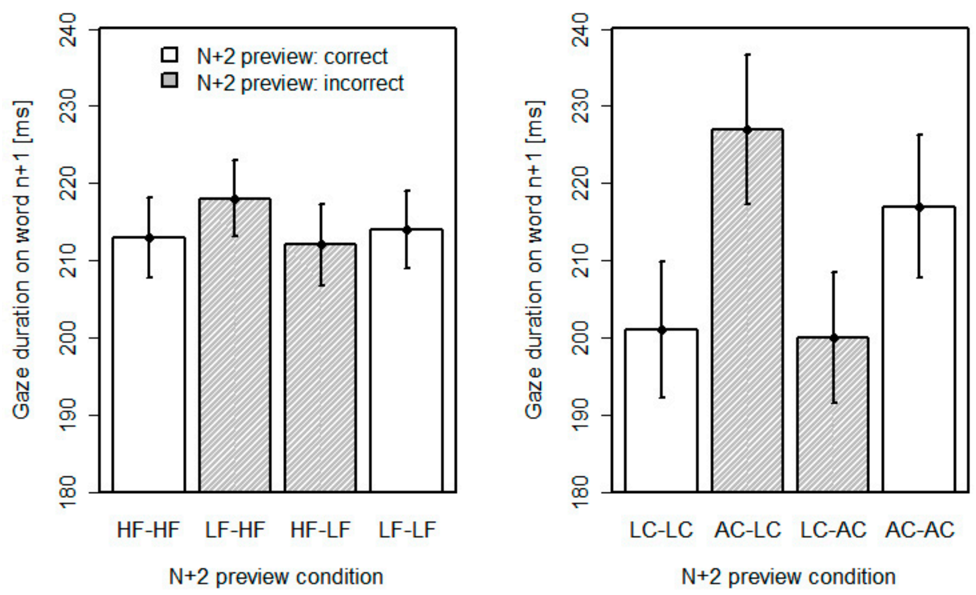

Figure 4.10 Comparison of change and no-change conditions in Experiment 3 (left panel) and Experiment 4 (right panel). Plotted are the mean GDs on word n+1 for the four different preview conditions of word n+2, two conditions with visual change of the n+2 display (grey bars) and two without change (white bars).

lation of word *n*+2, we obtained consistent evidence for delayed PoF effects on word *n*+1. Given that a high proportion of *n*+1 fixations may be mislocated, the main effect of *n*+2 pre-boundary difficulty argues against attention and processing being restricted only to the intended saccade target (i.e., word *n*+2) during mislocated fixations on word *n*+1. Target word *n*+2 processing such as an immediacy effect or PB was not obtained before word *n*+2 was finally fixated. Moreover, PB was distinguished in the presence of a strong immediacy effect of the *n*+2 post-boundary difficulty confirming that the paradigm is suitable to dissociate different sources of processing in one individual fixation duration. Experiment 4 even revealed an effect of the *n*+2 pre-boundary difficulty on the target word *n*+2. If word *n*+1 was skipped, the first fixation after crossing the boundary landed directly on word *n*+2 and showed a delayed PoF effect similar to the one observed if word *n*+1 was the first word fixated after crossing the boundary.

4.5.1 Replicating evidence of *n*+2 preprocessing in the perceptual span

Although it is broadly accepted that the size of the perceptual span during reading extends about three letters to the left and up to 15 letters to the right from a given fixation (McConkie & Rayner, 1976) there is still an active debate on how parafoveal information of not-yet-fixated words affect eye movements during reading. We want to shortly summarize three rather general conclusions of the present experiments. First, the results replicated some earlier findings of previewing word *n*+2 in the *n*+2-boundary paradigm (see Chapters 2 and 3). The effect of the *n*+2 pre-boundary difficulty on word *n*+1 and the PB interaction on word *n*+2 are indicative for information processing up to word *n*+2 and challenge the null effects reported in other studies.

Second, the present results suggest that the *n*+2 preview effects were not merely due to perceptual disruption in the *n*+2-boundary paradigm when word *n*+2 was changed after crossing the boundary (Inhoff et al., 1998; O'Regan, 1990). Figure 4.10 illustrates the four condition means in both experiments for fixations on word *n*+1. Post-hoc comparisons using sliding difference contrasts across the four preview conditions showed a significant difference in fixation durations between the two conditions in which the display of word *n*+2 was changed[3]. Such a difference cannot be attributed to the display change itself. Therefore, the results of Experiment 3 and 4 exclude one possible interpretation of the *n*+2 preview effect on the post-boundary word *n*+1 (see also 2.4.3).

Third, the lack of evidence for perceptual display-change effects further suggests that in

[3] Comparison of the two change conditions. GDs word *n*+1: Experiment 3: $b = -.03$, $SE = .01$, $t = -2.01$; Experiment 4: $b = -.13$, $SE = .03$, $t = -5.13$; GDs word *n*+2: Experiment 3: $b = .07$, $SE = .01$, $t = 5.19$; Experiment 4: $b = .18$, $SE = .02$, $t = 8.29$. The reported difference is positively coded on the *n*+2 pre-boundary difficulty. As we only look at trials in which the display was changed, it likewise negatively codes the *n*+2 post-boundary difficulty. The negative sign of the estimated slope for word *n*+1, therefore, reflects the delayed POF effect, the positive sign for the estimated slope for word *n*+2 is due to the stronger impact of post-boundary difficulty if word *n*+2 is fixated.

Experiment 3 word *n*+2 must have been preprocessed up to its lexical level. Finding lexical PoF effects stands in contrast to research with the *n*+1-boundary paradigm (e.g., Henderson & Ferreira, 1993; Kennison & Clifton, 1995; but see Hyönä & Bertram, 2004). Such results are in closer agreement with evidence from a corpus analysis documenting influences of the frequency of short words *n*+2 in single fixation durations on a currently fixated word *n* (Risse et al., 2008).

4.5.2 Delayed PoF effects: Evidence against mislocated immediacy processing

Restricted to three letters length, the post-boundary word *n*+1 was skipped very often (Gautier et al., 2000) and should, therefore, be a good candidate for mislocated fixations if the intended skip failed (Engbert & Krügel, 2010). In fact, if word *n*+1 was fixated, none of the experiments showed an influence of current word processing in *n*+1 fixation durations. The consistent absence of an immediacy effect of the lexical status and hence the processing difficulty of word *n*+1 suggests that *n*+1 processing was already terminated in parafoveal vision prior to its fixation. Any direct fixation should, therefore, be superfluous and probably reflects oculomotor error rather than intended saccade targeting.

Several studies have argued that during mislocated fixations the intended saccade target is processed and not the fixated word (Angele & Rayner, 2011; Drieghe et al., 2008; Rayner et al., 2004). Thus, mislocated fixations on word *n*+1 should reflect an immediacy effect of processing word *n*+2 and, given preprocessing of word *n*+2, an additional mislocated PB effect. The results of the present studies, however, indicated that only the processing difficulty of word *n*+2 before the boundary modulated the post-boundary fixation on word *n*+1. In the presence of an easy *n*+2 target, GDs on word *n*+1 were up to 27 ms longer if preview of word *n*+2 had been difficult prior to crossing the boundary (e.g., written in alternating case), even though the preview was not available anymore in parafoveal vision. The effect of *n*+2 pre-boundary difficulty clearly suggests a genuine PoF effect which is delayed into (mislocated) fixations on word *n*+1.

Previous studies interpreted PoF effects as un-intended refixations while attention and processing was confined to the neighboring target word (Drieghe et al., 2008; Rayner et al., 2004). The present study calls this interpretation into question. Finding a delayed PoF effect in the absence of any post-boundary target word processing argues against oculomotor artefacts while maintaining serial lexical processing. It seems unlikely that oculomotor error leading to failed skipping should result in a significantly different processing situation than if it leads to un-intended refixations.

Genuine PoF effects have been discussed as evidence for cross-talk of processing several words in parallel and thus in favor for distributed attention. The present findings are, in principle, consistent with the idea of PoF cross-talk. However, the delayed PoF effect suggests that the spatial eccentricity of parafoveal information influences its temporal availability and thus the time at which it shows an impact on eye-movement measures such as fixation durations. Such a temporal delay conforms to findings from Lee, Legge, and Ortiz (2003) who showed that word frequency effects occur later in time with increasing eccentricity of a target word from the current fixation position (see also Schiepers, 1980). Delayed PoF effects are also in agreement with evidence of decreasing visual acuity in parafoveal vision reducing the processing efficiency of parafoveal relative to foveal targets (Bouma, 1973; O'Regan, 1990; Rayner & Morrison, 1981). Given that word *n*+2 processing difficulties need more time to accumulate, it seems plausible to assume a delay in *n*+2 PoF effects such that they occur in fixation durations not before the boundary has been crossed.

However, some results are also difficult to reconcile with a strict cross-talk assumption. If there was cross-talk up to word *n*+2 then effects of the direct fixation neighbor should be even stronger. Fixating word *n*+1, one would expect an additional PoF effect of the adjacent word *n*+2. In the present paradigm, this reflects the mislocated immediacy effect of *n*+2 processing, a result we did not obtain. As fixation durations on word *n*+1 were relatively short it could be argued that the parafoveal information of the neighboring word *n*+2 was not available in time to significantly prolong fixation durations on word *n*+1. In some cases, the eyes might have already left word *n*+1. It must be noted that such an interpretation affords that saccades can be initiated relatively independent of (parafoveal) word processing. Further implications will be discussed in more detail below and in the General Discussion (see 5.3).

4.5.3 The time course of parafoveal processing in the perceptual span

The *n*+2-boundary paradigm provides the possibility to track *n*+2 preview effects across a three-word target region. N+2 preview effects must stem from preprocessing word *n*+2 during pre-boundary fixations. However, the consequences of such preprocessing were not locally restricted but distributed across the two post-boundary words *n*+1 and *n*+2. More specifically, the present results suggest the following picture of processing inside the perceptual span: Whereas preprocessing word *n*+1 in parafoveal vision elicits a direct PoF effect in fixation durations on the pre-boundary word *n*, preprocessing the adjacent word *n*+2 occurs on the same pre-boundary fixation(s) but affects oculomotor control with some delay. Preprocessing a difficult preview in parafoveal vision evokes costs in the current and/or next fixation. In addition, preprocessing the correct preview caused significant benefit in the time needed to process word *n*+2 if it was finally fixated.

Dissociating preview cost and benefit, therefore, indicates that preprocessing in the perceptual span affects the oculomotor system at least via two different routes. On the one hand, preprocessing word *n*+2 during pre-boundary fixations reduces its local processing demand. Integrating correct preview information across saccades leads to benefits in fixation durations when the word is finally fixated. On the other hand, preprocessing word *n*+2 can also lead to a non-local increase in processing demand. A difficult *n*+2 preview can prolong fixation durations and adaptively modulate saccade programming even prior to the location of difficulty.

Two other recent studies investigated the time course of processing inside the perceptual span. Wang, Inhoff, and Radach (2009) tested whether costs due to parafoveal masking have to be resolved locally as predicted from SAS models. Consistent with the present results, they obtained non-local effects that suggested distributed attention across a broader region than the single word unit. Angele and Rayner (2011; also see Angele et al., 2008) implemented a similar logic in two boundary studies manipulating preview of both word *n*+1 and *n*+2. They obtained weak evidence for previewing word *n*+2 only if word *n*+1 preview was available, suggesting that the processing difficulties of a nonword *n*+1 prevented attention to reach onto word *n*+2.

Whereas Wang et al. did not investigate previewing word *n*+2 and thus implemented a paradigm that substantially differed from the present experiments, Angele and Rayner's results may be more suitable for a comparison. However, we did not obtain that *n*+1 processing difficulties impeded preprocessing of word *n*+2. In contrast, manipulating the lexical status of word *n*+1 as one possible indicator of its processing difficulty, the more difficult content word often increased the size of word *n*+2 preview effects. Given parallel distributed processing this counterintuitive finding could be explained as follows: As the lexical status of word *n*+1 elicits a PoF effect on pre-boundary fixations on word *n* with longer fixation durations if word *n*+1 is a content word, participants spent considerably more time on the pre-boundary word *n* in content word than in function word sentences. Additional processing time on word *n* likewise leads to additional preprocessing time of word *n*+2 and may compensate for potential disadvantages due to the higher parafoveal load imposed by content words. Presenting nonwords *n*+1 in close parafoveal vision as was the case in the Angele and Rayner study might encourage a different processing strategy such as suppressing effective preview further to the right of the nonword.

4.5.4 Conclusions

The present experiments support the notion that fixation durations reflect not only the processing difficulty of the word currently fixated but also of not-yet-fixated words to the right of it. Processing in the perceptual span seems to be non-local and broadly distributed across the three-word target region investigated here. Moreover, the results provide experimental evidence against mislocated fixations mimicking PoF cross-talk in the *n*+2-boundary paradigm. Counter to the notion of oculomotor error, it could be shown that the first fixation after the boundary depends on the pre-boundary difficulty of word *n*+2. Dissociating later preview benefit from such (incorrect) preview cost argues against a strict confinement of processing only one word at a time. The evidence for a delayed PoF effect on the post-boundary word *n*+1 is consistent with distributed attention guiding parallel word processing and the notion of decreasing processing efficiency with increasing eccentricity from the current fixation location. More distant parafoveal processing difficulties seem to accumulate slower and, therefore, affect eye movements with a certain delay. Implications for computational models of eye-movement control will be outlined in the General Discussion (5.2).

CHAPTER 5
GENERAL DISCUSSION AND FURTHER OUTLOOK

A series of four experiments investigated parafoveal processing close to the spatial limits of the perceptual span. Using the *n*+2-boundary paradigm, Experiment 1 and 2 reliably demonstrated that given a short three-letter word *n*+1 even the subsequent word *n*+2 is effectively previewed. Although this is in agreement with the spatial extent of the perceptual span during reading, there are also studies that do not reinforce preprocessing word *n*+2. Such differences may be linked to various experimental details, but also to language-specific characteristics (see 5.1).

The present work aimed to go beyond mere existence proofs of previewing words at such spatial distances. In fact, Experiment 3 and 4 were designed to dissociate the sources of long-range preview effects in a single analysis and to track their impact across a three-word target region. The same manipulation ruled out oculomotor error in the SAS framework as the cause of non-locally distributed *n*+2 effects. In this respect, the results have direct implications for models of eye-movement control during reading (see 5.2) and contribute to the debate on the time course of word processing inside the perceptual span (see 5.3).

5.1 Differences in parafoveal processing between languages

The present experiments reliably document previewing word *n*+2. Such results are in agreement with findings from the moving-window paradigm indicating that processing in the perceptual span can comprise preprocessing up to word *n*+2 (Rayner et al., 2009). However, there are also studies that did not find evidence for *n*+2 preview effects (Rayner et al., 2007; Angele et al., 2008). Some studies suggest that word length of the intermediate word *n*+1 plays a crucial role (Risse et al., 2008; but see Angele & Rayner, 2011). As mentioned in Chapter 2, further possible reasons may be differences in statistical power or skipping biases of the pre-boundary word *n*.

Yet, it is also plausible to assume additional differences between languages. Some languages may favor more broadly distributed attention and thus more parallel oriented reading strategies to reach an optimal concurrence of new information input and word-into-sentence integration processes. In Chinese, for example, the density of information is increased within the square-shaped Chinese characters and the typical word length is reduced compared to alphabetic languages. This may encourage the processing of more than one word at a time. In fact, it could be shown that Chinese readers effectively used preview of word *n*+2 (Yan et al., 2011; Yang et al., 2009).

In the present series of experiments German native speakers were reading German sentences. One characteristic about written German is that the initial letter of nouns is always capitalized. In contrast to English, identification of purely visual features of the initial letter can provide important information about the word class of an upcoming word and narrows down the amount of possible word candidates. Manipulating the lexical status of word *n*+1 may have confounded an orthographic capitalization effect. Function words were conjunctions or prepositions whereas content words were nouns with an upper-case initial letter. Any preview effects that were attributed to the parafoveal processing difficulty of word *n*+1 (e.g., the *n*+1 PoF effect) could likewise be originated in low-level visual processing initiating the expectation of a more difficult German noun.

The present results indicated that previewing word *n*+2 was occasionally enhanced if word *n*+1 was the more difficult content word (e.g., Experiment 2 and 3). This contradicts findings in Chinese where increasing the parafoveal load by presenting a difficult, low-frequent one-character word *n*+1 reduced the PB effect of word *n*+2 (Yan et al., 2011). Angele and Rayner obtained no preview effects from word *n*+2 if word *n*+1 was presented as a nonword preview imposing a very high parafoveal load. In contrast, reducing the parafoveal load by presenting a short word *n*+1 (i.e., mostly the article "the") they observed some weak effects of previewing word *n*+2. Although presenting an orthographically illegal nonword might establish a different processing situation, it should be investigated more closely why using German nouns may result into preprocessing patterns that are opposite to the predictions from a parafoveal load hypothesis. At this point it seems undetermined how much variance in the results on parafoveal processing can be attributed to slight differences in the experimental paradigms used or must be explained by language-specific processing differences.

5.2 Implications for computational models of eye-movement control in reading

The goal of computational modeling is to translate theoretical assumptions into mathematical algorithms in order to evaluate whether such models have the ability to simulate the empirically observed behavior. Therefore, computational models on eye-movement control in reading differ in their implementation of how attention is allocated for word recognition. However, such models are necessarily much more complex and contain mechanisms that can interact and modulate fixation durations beyond the general predictions derived from SAS or PDA assumptions.

The most prominent SAS model is the E-Z Reader (Reichle, Pollatsek, Fisher, & Rayner, 1998; for the latest version see Reichle, Warren, & McConnell, 2009). The model implements word-by-word attention shifts. Moreover, lexical processing of the attended word directly controls the initiation of the next saccade. Fixating word *n*, the completion of a first familiarity check (L1) triggers a saccade program to the neighboring word *n*+1. The duration of L1 is determined by the difficulty of the currently processed word *n*. In parallel to saccade programming, word *n* is further processed. If its lexical access (L2) is reached prior to executing the saccade, (covert) attention is shifted to the next word *n*+1. Thus, word *n*+1 is preprocessed in parafoveal vision (i.e., L1 is started). If word *n*+1 is easy to process (i.e., L1 is terminated), the saccade to word *n*+1 may even be cancelled and re-programmed to target the next word *n*+2. During saccadic re-programming, parafoveal processing of word *n*+1 continues, and if completed, attention is shifted ahead onto word *n*+2. Therefore, given a short and easy word *n*+1, E-Z Reader can account for the present findings of *n*+2 PB, particularly if word *n*+1is skipped.

However, due to attention shifts following lexical access, parafoveal word *n*+2 information is not available before the previous words are completely processed. Any PoF effects are thus explained by oculomotor error leading to mislocated fixations (Drieghe et al., 2008; Rayner et al., 2004). Moreover, linking saccade programming directly to cognitive processing (i.e., the duration of L1) such mislocated fixations must reflect the processing demand of the currently attended word (i.e., the word *n*+2 target). The results of Experiment 3 and 4, however, showed that potentially mislocated fixations after failed skipping of word *n*+1 did not reflect the processing demand of the target word *n*+2 but its processing difficulty prior to crossing the boundary. Mislocated fixations fail to explain the delayed PoF effect in the framework of the E-Z Reader model.

Reichle, Rayner, and Pollatsek (2003) extended E-Z Reader by a pre-attentive visual stage (V) preceding lexical word processing. Visual word features inside the perceptual span are processed in parallel and are assumed to guide word segmentation processes and thus saccade programming. Moreover, the duration of this stage reflects information transmission from the retina to the primary visual cortex where the representation of only the attended word is supposed to be lexically processed. Estimating the transmission time at 50 ms (Pollatsek et al., 2006), in Experiment 3 and 4, the representation of the target word *n*+2 will become available on (mislocated) *n*+1 fixations with a certain delay. Therefore, during the first 50 ms of fixating word *n*+1 the old pre-boundary representation of word *n*+2 prior to crossing the boundary may still be processed. If L1 can be finished in this time window then *n*+1 fixation durations could reflect the pre-boundary difficulty of word *n*+2 rather than its post-boundary processing demand.

The probability of finishing L1 of an *n*+2-preview representation in the early stage of the *n*+1 fixation is higher if the *n*+2 pre-boundary difficulty was easy (i.e., HF or LC preview). Reflecting some kind of memory buffer, the visual stage is, however, constantly overwritten and updated with the new information. If word *n*+2 is the more difficult LF or AC preview, the probability of finishing its longer L1-stage prior to any update from the visual stage is drastically reduced. Therefore, a reliable proportion of *n*+1 fixations should "benefit" from replacing the difficult *n*+2 preview with an easy *n*+2 target word. However, due to the higher proportion of re-starts of processing the new target word representation, fixation duration may still be longer than in case of an easy *n*+2 preview. Thus, although mislocated fixations cannot explain the delayed PoF effect within the E-Z Reader framework, the pre-attentive visual stage might, in principle, account for such effects. If it is assumed that parafoveal processing can reach a level in which programming a saccade will not be cancelled anymore even if a new and more difficult representation is transmitted and available at some point prior to saccade execution, delayed effects of the *n*+2 pre-boundary difficulty are possible without the necessity of assuming parallel distributed processing.

Alternatively, assuming parallel processing inside the perceptual span difficulties of not-yet-fixated words are supposed to directly interact with foveal word processing and thus generate significant PoF cross-talk[4]. One straightforward theoretical formulation of this approach is the attention gradient hypothesis (Inhoff, Eiter, & Radach, 2005; Inhoff, Radach, & Eiter, 2006; Inhoff et al., 2000). Given an attentional gradient which is decreasing with increasing eccentricity from fixation position, its peak can be shifted towards regions that are difficult to process. If attention is assumed to be a limited resource (e.g., Alvarez, Horowitz, Arsenio, Dimase, & Wolfe, 2005; Kahneman, 1973) such a gradient shift will reduce the amount of resources left for processing the currently fixated word in foveal vision. Although we replicated evidence for a direct PoF effect of the neighboring word *n*+1, the according evidence for *n*+2 PoF effects were rather weak. Given the spatial distance of the parafoveal word *n*+2, accumulating *n*+2 difficulties might be slower and/or shifting the gradient across two subsequent words may take longer causing delays in *n*+2 relative to *n*+1 PoF effects.

Such a framework, although yet not implemented as a computational version, can explain positive PoF effects with longer fixation durations in the presence of a difficult parafoveal preview. However, some studies also obtained negative PoF effects (see Experiment 4) which should be likewise explained in a viable PDA model. Hyönä and Bertram (2004) argued that both positive and negative PoF effects were compatible with the notion of parallel processing and of parafoveal difficulties acting like a magnet. If several words are processed in parallel, depending on the distance between fixation position and parafoveal target, such a magnet could either lead to a refixation of the pretarget word (i.e., positive PoF effect) or to immediately programming a saccade towards the region of difficulty (i.e., negative PoF effect). This attractive mechanism is of course too simple to explain the non-locally distributed effects found in the present experiments. But, as the authors argue, the concept of a magnetic effect of attraction is quite similar to the idea of process monitoring postulated by Kennedy (1998; see also Kennedy et al., 2002). From such a view, processing of all words inside the perceptual span in parallel is independently monitored, and any processing difficulties that are obtained can modulate ongoing processing.

[4] This interpretation results from the logic of interactions in the ANOVA approach and their interpretation as serial (i.e., independent/additive) or parallel (i.e., dependent/over- or underadditive) processes. However, as will be detailed below, parallel processes can also be envisioned as being independent, e.g., if we think of the CPU's (central processing units) of computers. Such an approach can be associated with assumptions on attention as a multiple resource (Navon & Gopher, 1979) and seems also connected to parallel processing in the SWIFT model.

Such a monitoring system guaranties a high flexibility in guiding eye movements conditional on foveal and parafoveal processing demand and may be the most powerful candidate to explain the diversity of effects found in the *n*+2-boundary paradigm.

Something similar to a process monitoring system is implemented in the SWIFT model (Engbert, Nuthmann, Richter, & Kliegl, 2005; Richter, Engbert, & Kliegl, 2006), a computational model based on the idea of graded attention distributed across the perceptual span. Word processing is achieved in parallel with decreasing processing efficiency as eccentricity from a given fixation position increases. An autonomous random saccade timer initiates saccade programs. To modulate fixation durations as a function of processing difficulty, such autonomous saccade programs are occasionally inhibited by ongoing word processing (about 10 % of simulated fixations; see Engbert, Longtin, & Kliegl, 2002). Therefore, inhibition of the autonomous timer can be considered as inhibition by process monitoring. However, in SWIFT inhibition is confined to foveal word processing only. More specifically, processing difficulties of fixated words are accumulated over the last 350 ms and proportionately delay the next saccade program. As a consequence, parafoveal word difficulties do not contribute to the amount of inhibition and cannot directly modulate fixation durations to generate PoF effects.

SWIFT might be capable of generating PoF effects due to its powerful target-selection mechanism[5]. Whether saccade-target selection can account for the complex pattern of *n*+1 and delayed *n*+2 PoF effects in the present studies should be evaluated in simulations[6]. A parsimonious solution to implement the present findings into the SWIFT model has first been proposed in Kliegl et al. (2007). If both foveal and parafoveal word difficulties contribute to inhibition delaying the random saccade timer, the SWIFT model may be able to generate the variety of non-local effects of parafoveally processing word *n*+1 and *n*+2 in the present experiments. If the amount of inhibition is assumed to be proportional to the processing activity of all words beyond the attentional gradient, than the foveal word should inhibit the most, followed by word *n*+1, and with least inhibition of word *n*+2. Therefore, SWIFT should predict the observed delay in the

[5] For randomly chosen long inter-saccadic intervals on a given word *n*, the likelihood of refixating word *n* may differ conditional on the difficulty of the neighboring word *n*+1. In the case of an easy word *n*+1, a long word *n* fixation might lead to near completion of processing word *n*+1 in parafoveal vision. Therefore, competition of becoming the next saccade target will occur mainly between word *n* and *n*+2. If word *n* wins, it will be refixated reducing the likelihood of observing single-fixation cases with long fixation durations prior to an easy *n*+1 preview. In contrast, if word *n*+1 is difficult, it likely remains an interesting competitor for becoming the next saccade target irrespective of the duration of word *n* fixations. Even long word *n* fixations might be followed by a saccade towards word *n*+1 resulting on average in longer single fixation durations on word *n* prior to difficult words *n*+1.

[6] Some theoretical considerations may already speak against this possibility. Target selection in SWIFT accounts for PoF effects by modulating the refixation probability of word *n*. Increasing the refixation probability likewise increases cumulative fixation duration measures such as GDs. As argued above, easy words *n*+1 result in a higher proportion of refixating word *n* which should increase GDs on word *n* prior to an easy word *n*+1, thus producing negative PoF effects. However, we observed positive *n*+1 PoF effects in the present studies only, and *n*+2 PoF effects even being delayed.

n+2 PoF effect. In fact, inhibition on the basis of processing inside the entire perceptual span would be a direct translation of the process monitoring account into a computational model of eye-movement control based on distributed word processing in reading.

5.3 Implications for the debate on the time course of lexical processing

Although only a small sub-selection of computational models were discussed above (see Reichle et al., 2003, for a comprehensive review on eye-movement models), this already emphasizes some general points that should be considered more precisely in the debate on PoF effects and serial or parallel word processing. Computational models are much more complex and differ on many more variables than only on whether attention is shifted serially or is distributed in parallel across the perceptual span. In this respect, the E-Z Reader model may be successful in explaining the delayed PoF effect by means of its pre-attentive visual stage instead of mislocated fixations, although lexical processing remains strictly serial. Thus, when interpreting PoF effects as evidence against or in favor for a particular time-course assumption of lexical processing, it seems particularly mandatory to carefully distinguish between the theoretical approaches of SAS and PDA and how they are implemented into computational versions of the models .

More specifically, to account for both temporal and spatial aspects of eye-movement control during reading computational models have to mathematically translate assumptions not only on the time course of word processing but also on how such higher-level processing can affect the specific timing of when to move the eyes further in the text. Thus, the interplay between cognition and the oculomotor system has to be specified. As outlined above, in E-Z Reader a saccade is programmed when word processing reaches a certain threshold demarking a successful check of the word's familiarity (i.e., L1). Thus, besides shifting attention serially from one word to the next saccade programming is also directly triggered by ongoing cognitive processing (i.e., direct cognitive control). However, results of parafoveal processing in a reading-like visual-search task (Trukenbrod & Engbert, submitted) reveal an asymmetry in the adaptation of fixation durations to changes in processing difficulty that seems incompatible with the assumption of complete direct control. In fact, in a parallel processing model such as SWIFT saccadic movements are triggered autonomously and are only indirectly inhibited by ongoing processing (i.e., indirect cognitive control).

Deriving predictions of serial or parallel processing on the basis of fixation durations always necessitates unambiguous assumptions about how processing controls oculomotor timing. For example, interpreting PoF effects as cross-talk implies that word *n* processing can be slowed down if word *n*+1 interferes with processing word *n* and processing of word *n* determines when to program the next saccade. In other words, PoF cross-talk implies that foveal word processing directly triggers saccade programming and thus establishes direct cognitive control as employed

attention / timing	**serial processing** (attention shifts)	**parallel processing** (attention gradients)
direct control (trigger: cognition)	**E-Z Reader**	
indirect control (trigger: auton. timer)		**SWIFT**

Table 5.1 Two dimensional characterization of eye-movement models in reading. As two examples, the E-Z Reader and the SWIFT model are categorized according to the time course of attention (horizontal axis) and how saccadic timing is controlled (vertical axis). The 2 x 2 pattern is, however, oversimplified as the dimensions most likely reflect continuous variations of the respective categories.

in E-Z Reader. The difference to E-Z Reader would be that also parafoveal processing difficulties are able to affect foveal word processing. And this seems only possible if more than one word is processed at the same time.

However, not all PDA models assume direct cognitive control as outlined above. SWIFT is based on the concept of indirect cognitive control with independent process monitoring (i.e., foveal inhibition) influencing the otherwise autonomously triggered saccade programs. It might be important to mention that even if additional parafoveal inhibition was applied in SWIFT as suggested in 5.2, this would not reflect the concept of cross-talk between processing words in parallel. In fact, processing under the attention gradient, although running in parallel, is in SWIFT conceptualized as being independent (i.e., no normalization of the area below the gradient). Processing difficulties feed into the monitoring system which then controls the action. As such, PDA models can generate PoF effects without actually implementing cross-talk between word processing. Again, this emphasizes the need to specify the relation between word processing and saccade timing when interpreting the existence or absence of PoF effects as evidence for or against serial or parallel processing during reading.

As a further example of the independence between processing and timing assumptions, Engbert and Kliegl (2001) investigated the relaxation of the strict coupling of cognition and saccade timing in SAS models such as the E-Z Reader. They tested the possibility of adding autonomously triggered saccades to the framework of serial word processing. With attention confined to one word at a time, simulations provided support for the distribution of fixation durations during reading being best described if not all saccades were completely determined by lexical access processes. Although this approach reflects a mixture of control with some saccades being determined by lexical processing whereas others are not, it shows that different assumptions on the time course of word processing can be flexibly combined with different assumptions on the timing of saccades. In principle, SAS models with pure indirect control are also feasible. Attention could be shifted serially from word to word conditional on lexical completion of word recognition processes with the processing difficulty of the attended word inhibiting the next saccade. Both versions would add some degree of flexibility to SAS models with respect to the localization of preview effects. Whether this could explain the delayed PoF effect in the present studies is an interesting question for future research and further simulations.

In summary, computational models in reading can in principle be located in a two-dimensional space consisting of the time course of word processing and the control of saccadic timing. Processing could either be serial or parallel, and saccadic control could either be direct or indirect. As Table 5.1 illustrates, E-Z Reader and SWIFT would be assigned to opposite positions on the diagonal thus indicating that the models differ not only on one but on both dimensions. Moreover, the dimensions seem to be rather continuous than discrete such that mixed forms and hybrid versions are conceivable. This suggests that attempts of testing SAS versus PDA on the basis of fixation durations in reading can only be preliminary and inaccurate as long as hypotheses do not include precise assumptions on the underlying processes of saccadic timing. On the one hand, this emphasizes the importance of computational models that have to maintain such a high precision level in defining each of its constituent processes to simulate eye-movement data in real time. On the other hand, as there seem to be various possibilities of mathematical translations of a more abstract psychological and/or theoretical concept, this likewise emphasizes the need to experimentally evaluate and investigate the implementation of components installed in computational models.

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APPENDIX

Post-hoc estimation of display changes in the present experiments

In the boundary paradigm, the gaze-contingent replacement of the preview with the correct target word is supposed to occur during a saccade in which visual perception is suppressed (Matin, 1974). However, sometimes participants report to have noticed display changes when asked at the end of the experiment. White, Rayner, and Liversedge (2005) compared two groups of participants in the *n*+1-boundary paradigm, one group being unaware of the experimental manipulation and the other having noticed changes. They showed that participants who are aware of such changes exhibit stronger PB effects of the neighboring word *n*+1 and cautioned against interpreting such data as long as the nature of the differences between groups is not yet understood. Therefore, in the present work, participants who noticed changes during the experiment were excluded from all analyses.

In GCDC paradigms, the target word is usually replaced as soon as the x-coordinate of the monitored eye (mostly the right eye) exceeds the critical x-coordinate of the invisible boundary. This commonly defines the online criterion triggering the command of replacing the target word. In the experiments reported here both eyes were monitored. Thus, the eye that first exceeded the boundary location was used to trigger the display change. When the online criterion for triggering the display change was met, the command of replacing the sentence was executed and an according message was saved to the data file. Although this message can be read out from the Eyelink system without time-delays (cf. SR Research Ltd., 2006) and thus provides an event-sensitive time stamp, the actual replacement of the target word on the participants' monitor will be delayed. Using a CRT-monitor with a 150 Hz refresh rate a refreshing cycle took on average 7 ms. Thus, depending on the spatio-temporal position within the refresh cycle at the moment of giving the command to replace the sentence with the correct target word, some amount of time has to be added to the time stamp from the message file to approximate the time at which the display change eventually occurred on the monitor and could have been detected by the participants. In order to arrive at a close approximation of the time of display change on the monitor, the following estimation was made for each individual trial.

In a first step, the time needed to complete the current refresh cycle at the moment of the first eye crossing the boundary was computed. More specifically, as sentence presentation was synchronized with the monitor's refresh cycle, the cathode ray of the monitor was close to the horizontal middle axis at the beginning of each sentence presentation. Estimating the duration of one complete refresh cycle to 7 ms, the position of the ray at the time of crossing the boundary relative to its position at sentence presentation could be calculated. Based on this information, the time needed to complete this cycle was approximated. This was then added to the time stamp of when the internal display change command was executed. The result can be viewed as a post-hoc estimation of the time the word change was terminated on the monitor screen and was taken to select valid display change trials.

Post-hoc selection of valid trials

Valid trials were defined as trials in which the invisible boundary located at the end of the pre-boundary word *n* was crossed with a forward saccade launched from a position to the left and landing to the right of the boundary. In addition, the replacement of the target word on the monitor should be terminated before the critical saccade offset. Since reading was binocular only trials were selected in which both eyes crossed the boundary in a forward saccade. The rationale of such a conservative binocular selection criterion is that in a binocular reading situation both eyes run the risks to perceive the replacement of the target word n+2. Excluding trials only on criteria concerning the right eye would leave us with at least some trials in which the left eye is ahead of the right eye and might thus have detected the display change. Therefore, selecting valid trials considering the behavior of both eyes is more adequate in binocular reading situations than focusing on the right eye only.

Importantly, display change criteria were also applied to the identical preview condition. Although in the identical preview condition the replacement of the target word by itself was not expected to be visually perceived since it resembles nothing else than what occurs during a periodically refresh of the monitor screen, the reason of likewise discarding “invalid” display change trials in the identical preview condition was to avoid selection differences between the different preview conditions. For instance, trials in which a fixation is close to the end of word *n* and thus likely to elicit the display change by crossing the boundary during a fixational drift movement are removed from the data set of all preview conditions, not selectively for the incorrect preview condition.