

Temporal and spatial aspects of eye-movement control

From reading to scanning

Hans Arne Trukenbrod



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2nd reviewer: Prof. Dr. Felix Wichmann

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Abstract

Eye movements are a powerful tool to examine cognitive processes. However, in most paradigms little is known about the dynamics present in sequences of saccades and fixations. In particular, the control of fixation durations has been widely neglected in most tasks. As a notable exception, both spatial and temporal aspects of eye-movement control have been thoroughly investigated during reading. There, the scientific discourse was dominated by three controversies, (i), the role of oculomotor vs. cognitive processing on eye-movement control, (ii) the serial vs. parallel processing of words, and, (iii), the control of fixation durations.

The main purpose of this thesis was to investigate eye movements in tasks that require sequences of fixations and saccades. While reading phenomena served as a starting point, we examined eye guidance in non-reading tasks with the aim to identify general principles of eye-movement control. In addition, the investigation of eye movements in non-reading tasks helped refine our knowledge about eye-movement control during reading. Our approach included the investigation of eye movements in non-reading experiments as well as the evaluation and development of computational models.

I present three main results : First, oculomotor phenomena during reading can also be observed in non-reading tasks (Chapter 2 & 4). Oculomotor processes determine the fixation position within an object. The fixation position, in turn, modulates both the next saccade target and the current fixation duration. Second, predictions of eye-movement models based on sequential attention shifts were falsified (Chapter 3). In fact, our results suggest that distributed processing of multiple objects forms the basis of eye-movement control. Third, fixation durations are under asymmetric control (Chapter 4). While increasing processing demands immediately prolong fixation durations, decreasing processing demands reduce fixation durations only with a temporal delay. We propose a computational model ICAT to account for asymmetric control. In this model, an autonomous timer initiates saccades after random time intervals independent of ongoing processing. However, processing demands that are higher than expected inhibit the execution of the next saccade and, thereby, prolong the current fixation. On the other hand, lower processing demands will not affect the duration before the next saccade is executed. Since the autonomous timer adjusts to expected processing demands from fixation to fixation, a decrease in processing demands may lead to a temporally delayed reduction of fixation durations. In an extended version of ICAT, we evaluated its performance while simulating both temporal and spatial aspects of eye-movement control.

The eye-movement phenomena investigated in this thesis have now been observed in a number of different tasks, which suggests that they represent general principles of eye guidance. I propose that distributed processing of the visual input forms the basis of eye-movement control, while fixation durations are controlled by the principles outlined in ICAT. In addition, oculomotor control contributes considerably to the variability observed in eye movements. Interpretations for the relation between eye movements and cognition strongly benefit from a precise understanding of this interplay.

Zusammenfassung

Blickbewegungen stellen ein wichtiges Instrument dar, um kognitive Prozesse zu untersuchen. In den meisten Paradigmen ist allerdings wenig über die Entstehung von Sakkaden und Fixationen bekannt. Insbesondere die Kontrolle der Fixationsdauern wurde häufig außer acht gelassen. Eine wesentliche Ausnahme stellt die Leseforschung dar, in der sowohl zeitliche als auch räumliche Aspekte der Blickbewegungssteuerung im Detail betrachtet wurden. Dabei war der wissenschaftliche Diskurs durch drei Kontroversen gekennzeichnet, die untersuchten, (i), welchen Einfluss okulomotorische bzw. kognitive Prozesse auf die Blicksteuerung haben, (ii), ob Worte seriell oder parallel verarbeitet werden und, (iii), wie Fixationsdauern kontrolliert werden.

Die vorliegende Arbeit zielt im wesentlichen darauf ab, die Dynamik von Fixationssequenzen zu erforschen. Ausgehend von den Erkenntnissen beim Lesen untersuchten wir Blickbewegungen in Nichtlese-Aufgaben, mit dem Ziel allgemeine Prinzipien der Blicksteuerung zu identifizieren. Zusätzlich versuchten wir mit Hilfe dieser Aufgaben, Erkenntnisse über Prozesse beim Lesen zu vertiefen. Unser Vorgehen war sowohl von der Durchführung von Experimenten als auch der Entwicklung und Evaluation computationaler Modelle geprägt.

Die Hauptbefunde zeigten: Erstens, okulomotorische Phänomene des Lesens lassen sich in Suchaufgaben ohne Wortmaterial replizieren (Kapitel 2 & 4). Dabei bestimmen okulomotorische Prozesse die Fixationsposition innerhalb eines Objektes. Diese wiederum beeinflusst das nächste Sakkadenziel sowie die Fixationsdauer. Zweitens, wesentliche Vorhersagen von Modellen, in denen Blickbewegungen von seriellen Aufmerksamkeitsverschiebungen abhängen, konnten falsifiziert werden (Kapitel 3). Stattdessen legen unsere Erkenntnisse nahe, dass die Blicksteuerung von der parallelen Verarbeitung mehrerer Objekte abhängt. Drittens, Fixationsdauern werden asymmetrisch kontrolliert (Kapitel 4). Während hohe Verarbeitungsanforderungen Fixationsdauern unmittelbar verlängern können, führen niedrige Verarbeitungsanforderungen nur zeitlich verzögert zu einer Reduktion. Wir schlagen ein computationales Modell ICAT vor, um asymmetrische Kontrolle zu erklären. Grundlage des Modells ist ein autonomer Zeitgeber, der unabhängig von der momentanen Verarbeitung nach zufälligen Zeitintervallen Sakkaden initiiert. Unerwartet hohe Verarbeitungsanforderungen können die Initiierung der nächsten Sakkade hinauszögern, während unerwartet niedrige Verarbeitungsanforderungen den Beginn der nächsten Sakkade nicht verändern. Der Zeitgeber passt sich allerdings von Fixation zu Fixation neuen Verarbeitungsanforderungen an, so dass es zu einer zeitlich verzögerten Reduktion der Fixationsdauern kommen kann. In einer erweiterten Version des Modells überprüfen wir die Kompatibilität ICATs mit einer realistischen räumlichen Blicksteuerung.

Die Ähnlichkeit von Blickbewegungsphänomenen über Aufgaben hinweg legt nahe, dass sie auf allgemeinen Prinzipien basieren. Grundlage der Blicksteuerung ist die verteilte Verarbeitung des visuellen Inputs, während die Kontrolle der Fixationsdauer auf den Prinzipien von ICAT beruht. Darüber hinaus tragen okulomotorische Phänomene wesentlich zur Variabilität der Blicksteuerung bei. Ein Verständnis dieses Zusammenspiels hilft entscheidend den Zusammenhang von Blickbewegungen und Kognitionen besser zu verstehen.

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Chapter 1

General introduction

Human life is characterized by vision. It guides us through our environment, helps us find food and avoid life-threatening situations. But vision is not a passive, bottom-up, interpretation of the visual world that proceeds hierarchically from the retina to the cortex until a detailed representation is computed. Vision is a dynamic process consisting of recurrent connections with both forward and backward projections between cortical and subcortical areas. Visual processing incorporates short-term semantic memory in order to maintain a general sense of what is going on, generates predictions based on prior experience, interacts with motor systems (eye, head, body), and is modulated by other sensory modalities (Churchland, Ramachandran, & Sejnowski, 1994). This complexity renders possible the smooth execution of a diverse set of sophisticated tasks like reading, navigating a vehicle at high speed, or sports.

The oculomotor system plays a pivotal role in this process, since visual perception is strongly influenced by gaze direction (Findlay & Gilchrist, 2003). Visual acuity is highest at the center of gaze and decreases from the central part (fovea) towards the periphery. This inhomogeneity is maintained throughout the visual system so that projections away from the fovea receive less weighting in the entire cortex. But the role of the eyes is not purely passive. Instead, the eyes act as a motor system themselves and movements of the eye are visually guided responses that bring informative areas into the center of gaze *just-in-time* (Ballard, Hayhoe, & Rao, 1997; Land & Tatler, 2009). Even though informativeness depends on an observer's intentions and may change at any given moment the direction of gaze reveals underlying perceptual events, which can be linked to mental operations and the organization of complex behaviors. Thus, the oculomotor system provides a window to the mind and gives insights about perception, cognition, and behavior.

1.1 Computational models: Dealing with complex theories

The complexity of the oculomotor system and its connections to related processing systems, however, can barely be understood by verbal theorizing alone. As a possible solution, Fum, Del Missier, and Stocco (2007) recommended the development of computational models. Computational models represent simpler and abstract versions of the investigated process, restricted to their essential features while omitting unnecessary

details. The explicit formulation of a theory in the form of a computational model allows to investigate phenomena that are too complex or too difficult to deal with directly and supports theoretical progress at several levels (Fum et al., 2007; Lewandowsky, 1993).

Clarity and completeness. By definition, computational code cannot be vague. While seemingly intuitive verbal theories can turn out to be incoherent or ill-specified, implementation of a model reveals any hidden insufficiency of a verbal theory. All assumptions need to be identified, addressed, and tested. A running program requires that all variables are operationalized, relationships between variables need to be specified, and parameter values have to be set. The resulting computational model is a precise statement of a theory, where all hidden assumptions have been made explicit, including aspects which might otherwise be overlooked. Hence, “a running computational model [...] can be considered as a sufficiency proof of the internal coherence and completeness of the ideas it is based upon” (p. 136, Fum et al., 2007).

Exploration and evaluation. Computational models provide an excellent environment to explore and evaluate a theory. Models may consist of multiple subsystems interacting in a highly complex and dynamic way. While inference of a verbal theory is confined by the limits of human reasoning, running computational models generates explicit predictions that can be compared with behavioral data, without limitations due to the level of complexity. Furthermore, models provide a setting for experimentation and modification: Components can be deterministic or stochastic, dynamics of the model can be changed, and components can be en- or disabled. Many of these manipulations can impossibly be done with human subjects and results of successful simulations may point towards explanations otherwise obscured.

Serendipity and emergence. Computational approaches result in a better understanding of observed phenomena that is only accessible, when mechanisms are explicitly considered. The theoretical progress is often unexpected and may take several forms: the emergence of a single unifying principle that bridges a set of hitherto unrelated observations; results of a simulation that contradict commonsense expectations; or the interaction of simple local rules that generates complex and holistic behaviors. Theoretical progress gained by computational models leads to testable predictions, which in turn guide data collection.

According to Lewandowsky and Farrell (2010), consideration of behavioral data through verbal theorizing alone is insufficient. Instead, complex phenomena require (computational) models to be understood and explained. However, computational models on their own will not suffice either and the segregation of behavioral data and computational models needs to be overcome by constant interaction of both. Data need to result in theory development, while theories have to constrain data collection. By this criterion, both data gathering and theory building (in the form of computational models) play a critical role for scientific progress (Lewandowsky, 1993).

The work presented in the following chapters is committed to this way of thinking. The complexity of the oculomotor system and its manifold interactions with other systems requires a joint approach of computational modeling and experimental data collection. Since spatio-temporal aspects of eye guidance have been extensively investigated from a computational as well as from an experimental perspective during reading, models for the control of eye movements during reading served as a promising starting point. With

the objective to identify general principles for the control of eye movements across tasks, we tested predictions of existing models experimentally, refined theoretical assumptions, and validated new insights by implementing computational models. I begin with a brief introduction about eye movements, with a focus on eye guidance during reading. Next, I highlight the most important theoretical controversies that determined the development of eye movements models during reading, before presenting a detailed description of the currently most elaborate computational models, namely E-Z Reader (e.g., Reichle, Pollatsek, Fisher, & Rayner, 1998) and SWIFT (e.g., Engbert, Nuthmann, Richter, & Kliegl, 2005). The introduction ends with an overview of the conducted studies. Eye movement control in non-reading tasks related to each study is discussed in the corresponding chapters.

1.2 Eye movements

Eye movements represent an excellent tool to investigate cognitive processes, since gaze is continuously directed towards informative regions to gain visual input *just-in-time* (Ballard et al., 1997; Land & Tatler, 2009). Four types of eye movements support the acquisition of visual information: stabilization movements, smooth pursuit, vergence movements, and saccades (Findlay & Gilchrist, 2003). Visual stabilization of the retinal image during head and body movements is achieved by the *optokinetic* and *vestibulo-ocular* reflexes. Smooth pursuit movements track moving objects with the fovea and vergence movements select different depth planes. Since these types of eye movements were irrelevant for the tasks studied here, I focus on saccades in the remainder.

Saccades are “rapid jerk-like movements of the eyes” (p. 661, Findlay & Walker, 1999) that bring gaze onto informative parts of the visual field for closer examination. These movements are generated about 3–4 times per second, resulting in many tens of thousands of saccades over the course of a single day. Due to their frequent occurrence, saccades need to be fast and precise, which is achieved by their stereotyped and (semi-)ballistic nature (Harris & Wolpert, 2006). Most naturally occurring saccades tend to be only a few degrees in size (Bahill, Adler, & Stark, 1975), although some tasks afford larger orienting movements. In that case, saccades are usually accompanied by head and/or body movements (Land & Tatler, 2009). The duration of a saccade depends on its amplitude and is typically in the range of 20–50 ms. Since vision is hampered during saccades (Matin, 1974), information uptake is restricted to the time between two saccades (fixations). Other cognitive processes seem to continue without disruption during the execution of saccades (Irwin, 1998).

Each saccade is a motor act that involves a decision about *when* and *where* to move the eyes. Neurophysiologically, these events are (at least partially) based on independent systems (Carpenter, 2000; Findlay & Walker, 1999; Wurtz, 1996). Even after removing the uncertainty about *when* or *where* to move, saccade preparation takes about 150 ms (Rayner, 2009; Schall & Thompson, 1999) and proceeds in two stages (Becker & Jürgens, 1979). During an early labile stage (first 100 ms) saccades may be modified or even cancelled. After passing a point of no return at the beginning of the non-labile stage (last 50 ms), saccade parameters get fixed and saccades become resistant to further modifications.

Programming of saccades is not necessarily a sequential process and successive saccades may be programmed in parallel (McPeck, Skavenski, & Nakayama, 2000). Furthermore, visual processing continues during the programming of saccades and due to the close coupling of eye movements and attention, processing at the upcoming saccade target location is enhanced (Deubel & Schneider, 1996; Kowler, Anderson, Doshier, & Blaser, 1995; cf., Belopolsky & Theeuwes, 2009). While eye movements are preceded by attention shifts, it is possible to move attention covertly, without executing a saccade (Posner, 1980).

Fixations are moments of (relative) stability between two saccades during which gaze is held stationary.¹ Across tasks, fixations last on average between 200–300 ms, but individual fixations are highly variable and range from less than a hundred milliseconds to more than a second. Due to the inhomogeneity of the retina, the distance from the center of gaze has strong impact on the processing of visual input. Visual acuity is highest at the fovea (within 1° eccentricity), declines considerably in the parafovea (between 1° and 5° eccentricity), and is lowest in the periphery (beyond 5° eccentricity). The classification into fovea, parafovea, and periphery is arbitrary and solely based on descriptive convenience (Findlay & Gilchrist, 2003). In fact, visual acuity declines continuously as a function of eccentricity.

There are at least two reasons for the fixation-saccade strategy found in humans (Land & Tatler, 2009). The first reason results from the inhomogeneity of the visual field with a high resolution fovea. Humans would require a brain “some hundreds of thousands times larger than our current brain” (p. 5, Findlay & Gilchrist, 2003) to deal with a visual system that had the resolution of the fovea across the entire retina. The inhomogeneity of our visual system, thus, combines high resolution analysis in the fovea with the ability to monitor the remaining visual field. Furthermore, fixation-saccade strategies can be found throughout the animal kingdom (primates, fish, crabs, insects, and cuttlefish; Land, 1999) and can even be observed in animals without a well-defined fovea (e.g., goldfish). The need for a steady gaze across species arises from the relatively slow response times of photoreceptors. Cones on the retina of the human eye, for example, need about 20 ms to fully respond to a flash of light; thus, without fixations our visual world would basically be blurred.

Before turning to eye-movement control in reading, it is important to note that saccade programming and execution have been extensively investigated during the past decades. The previous section is far from exhaustive and limited to phenomena directly related to the upcoming sections. For a collection of recent reviews concerning eye movements see Liversedge, Gilchrist, and Everling (2011).

1.3 Eye-movement control during reading

Even though readers have the impression to smoothly and steadily move their eyes along a line of text, Javal (1879), referring to work that was later published by Lamare (1892), and Hering (1879) were the first to draw attention to the fixation-saccade strategy observed during reading (cited according to Wade, Tatler, & Heller, 2003). Since that time

¹The eyes are never perfectly still and miniature eye movements (microsaccades, drift, tremor) can be observed during fixations (Ciuffreda & Tannen, 1995).

extensive knowledge has been accumulated about eye movements during reading. In English and other alphabetic scripts, saccades have an average amplitude of about 7–9 character spaces and an average duration of about 30 ms (Findlay & Gilchrist, 2003). Letter space is commonly used as metric in reading, since saccades are invariant to different visual angles and primarily depend on the number of letters (Morrison & Rayner, 1981). Average fixation durations last about 200–250 ms, while individual fixations exhibit considerable variability. Several factors influence eye-movement statistics during normal reading. Average fixation durations and average saccade amplitudes, for example, vary with reading type (e.g., skimming vs. proof-reading; Just & Carpenter, 1987; Wotschack, 2009), text difficulty (Rayner & Pollatsek, 1989), reading skill (McConkie et al., 1991), and age (Rayner, Yang, Castelhana, & Liversedge, 2011). The impact of cognitive processing, however, is not limited to overall performance during reading. Properties of the text in the fovea and parafovea affect eye movements on a moment-by-moment basis. Before I turn to these moment-by-moment influences, I briefly present the nomenclature commonly used to describe modulations of individual fixations during reading.

1.3.1 Classification of eye movements

From an eye-movement perspective, reading alphabetic scripts is a well-specified task. Reading proceeds in a predefined direction and only a limited number of words compete as the next saccade target. Therefore, eye movements are frequently characterized relative to the target of a saccade. *Forward saccades* represent the most common movement and shift gaze from the currently fixated word_{*n*} to the next word_{*n*+1}. *Refixations* change the position of gaze within a word_{*n*}, which results in several successive fixations of the same word_{*n*}, and *skippings* move the eyes to subsequent text (word_{≥*n*+2}) without fixations on intermediate words. Although most saccades take the eyes forward along the line of text, about 15% of saccades return gaze to earlier passages. In most cases, these *regressions* aim at the preceding word_{*n*-1}, but gaze may also be directed precisely towards more distant words_{≤*n*-2} (Frazier & Rayner, 1982; Kennedy, 1983; Kennedy & Murray, 1987; Murray & Kennedy, 1988). In addition, *return sweeps* shift gaze from the end of a line to the beginning of the next. Interestingly, the first and the last fixation are generally located 5–7 letter spaces away from the line beginnings and endings. Thus, only 80% of the text typically falls within these extreme fixation positions (Rayner, 2009).

The preceding classification is based on target selection and emphasizes the role of different saccade types. Subsequent analyses usually include the probability and amplitude of different saccade types as well as the duration of the preceding and/or succeeding fixation. In contrast, other classifications focus on processing of individual words. *First fixations* represent all initial fixations on a word, while ignoring refixations. *Single fixations* consist of a subset of first fixations and refer to all cases, when a word is fixated once. Both the probability as well as the average duration of these measures is usually reported. In addition, *gaze durations* account for refixations and are given by the sum of all fixation durations on a word before leaving it. Finally, *total reading time* includes rereading a word after regressions. Note that in most experiments, analyses of eye movements are based on first-pass reading, which limits the analyses to the first encounter of a word without subsequent regressions. In summary, no measure on its own

suffices to describe the complex dynamics of eye guidance and usually a combination of target selection probabilities (skippings, regressions) and fixation duration measures (first, single, gaze) need to be considered.

1.3.2 Immediacy effects

Beyond the impact on eye movement statistics on overall performance, processing of individual words influences target selection and fixation durations on a moment-by-moment basis. *Immediacy effects* refer to modulations of eye movement control generated by processing of the fixated word_n. The three main determinants of processing are length, printed frequency, and predictability (or contextual constraint). Gaze durations on words increase with increasing length, decreasing frequency, and decreasing predictability (e.g., length & frequency: Just & Carpenter, 1980; predictability: Ehrlich & Rayner, 1981). Prolongations result from a combination of more refixations as well as longer fixation durations (e.g., length: McConkie, Kerr, Reddix, Zola, & Jacobs, 1989; frequency: Rayner & Duffy, 1986; predictability: Ehrlich & Rayner, 1981). Furthermore, short, high-frequent, and high-predictable words are skipped more often than their low-frequent, long, and low-predictable counterparts (e.g., length: Rayner, 1979; frequency: O'Regan, 1979; predictability: Ehrlich & Rayner, 1981). While word length may primarily influence eye guidance via the visual layout, predictability and frequency effects demonstrate the immediate influence of lexical processing on eye movements. In general, text processing of the fixated word affects eye guidance on a moment-by-moment basis at several levels. Comprehensive summaries of lexical, orthographic, phonological, semantic, and syntactic effects can be found in the reviews by Rayner (1998, 2009).

1.3.3 Lag & Parafoveal-on-Foveal effects

Modulations of eye guidance are not limited to the fixated word. Instead multiple words are processed during a single fixation. The *perceptual span* characterizes the area from which visual information is acquired during a fixation. Its upper limit is determined by visual acuity that declines from the fovea towards the periphery. In order to quantify the size of the perceptual span during reading, McConkie and Rayner (1975) developed the *moving window paradigm*, a gaze-contingent experiment. During each fixation, normal text is presented in a window around the center of gaze, while the remaining text is replaced by pseudo text. By varying size and shape of the window as well as the type of pseudo text, general properties of the perceptual span have been identified. In alphabetic scripts like English, the perceptual span is asymmetric and extends from about 3–4 letters to the left of fixation to about 15 letters to the right (Binder, Pollatsek, & Rayner, 1999; McConkie & Rayner, 1976). Thus, information from three to four words is extracted during an average fixation. In scripts like Hebrew that are read from right to left, the asymmetry reverses (Pollatsek, Bolozky, Well, & Rayner, 1981) and extends further to the left. Furthermore, the perceptual span is limited to the fixated line and no information from the line above or below fixation is extracted (Pollatsek, Raney, LaGasse, & Rayner, 1993). While word boundaries and shape information are acquired from the entire perceptual span, recognition of word-interior letters is limited to the ten central characters

(the number of letters varies somewhat with font size; Legge, Mansfield, & Chung, 2001; Legge et al., 2007). In line with this, masking central letters dramatically impairs reading performance. Small masks of three letters reduce reading rate and a seven letter mask, which extends across the entire fovea, makes normal reading almost impossible (Rayner & Bertera, 1979; Rayner, Inhoff, Morrison, Slowiaczek, & Bertera, 1981).

Several words are processed during a single fixation. As discussed earlier, immediacy effects reflect that lexical information is acquired from the fixated word. But what kind of information is obtained from the remaining words within the perceptual span? The *boundary paradigm* (Rayner, 1975), another gaze-contingent experiment, allows to investigate the preview accumulated before a word is fixated. Initially, preview of a target word is distorted by presenting another word, a nonword, or a random letter string. As soon as gaze crosses an invisible boundary, usually located immediately in front of the investigated word, the preview is replaced by the correct word. In general, readers spend more time fixating a target word after an invalid preview, even though they are (usually) unaware of the display change due to saccadic suppression. The size of the *preview benefit* is about 20–50 ms, but depends on the distance of the preview from the fixation position (Hyönä, 2011) and on the difficulty of the fixated word (i.e., foveal load; Henderson & Ferreira, 1990; Kennison & Clifton, 1995). Thus, more information is gained from a word, when the preceding fixation is close to the end of a “simple” (e.g., high-frequent) word. Note, integration of information across saccades is more than just matching of visual features. Reading proceeds without disruption when the case of letters is alternated between fixations (McConkie & Zola, 1979) and transposing two letters within a word yields more preview than substitution of the same letters by similarly shaped characters (Johnson, Perea, & Rayner, 2007).

Usage of the boundary paradigm revealed that readers obtain preview about word length (e.g., Inhoff, Starr, Liu, & Wang, 1998), orthographic code, in particular from the initial and final letters of a word (e.g., Briehl & Inhoff, 1995; cf., Inhoff, 1989b; Rayner, Well, Pollatsek, & Bertera, 1982), and phonological code (e.g., Pollatsek, Lesch, Morris, & Rayner, 1992). Even though valid preview is needed for fast lexical access during the subsequent fixation (Reingold, Reichle, Glaholt, & Sheridan, 2012), the degree to which words may be identified in parafoveal vision remains controversial. While morphological previews facilitate foveal processing in Hebrew (Deutsch, Frost, Pelleg, Pollatsek, & Rayner, 2003) and Chinese (Yen, Tsai, Tzeng, & Hung, 2008), they are not observed in English (e.g., Inhoff, 1989a; Lima, 1987) and Finish (Bertram & Hyönä, 2007). Likewise, semantic preview benefits have been found in Chinese (Yan, Richter, Shu, & Kliegl, 2009) but are absent in alphabetic scripts (e.g., Rayner, Balota, & Pollatsek, 1986). By combining the boundary paradigm with the presentation of a semantically related prime, Hohenstein, Laubrock, and Kliegl (2010), however, demonstrated that in principle it is possible to extract semantic information from the parafovea while reading alphabetic scripts. Recently, the boundary paradigm has also been used to study processing beyond the next word (Angele, Slattery, Yang, Kliegl, & Rayner, 2008; Kliegl, Risse, & Laubrock, 2007; Risse & Kliegl, 2011). Preview of the word after the next is acquired when it is preceded by a short word with three characters or less. The type of information acquired from distant words remains to be explored.

Finally, examining eye movements during normal reading, that is, without the presentation of gaze-contingent display changes, is also used to explore processing during a fixation. The observed influences are usually classified according to the word of origin. In addition to *immediacy effects*, which are generated by processing of the fixated word_{*n*}, *lag effects* refer to modulations generated by the preceding word_{*n-1*}, and *parafoveal-on-foveal* (PoF) effects originate from processing of the upcoming word_{*n+1*}. Kliegl, Nuthmann, and Engbert (2006; cf., Rayner, Pollatsek, Drieghe, Slattery, & Reichle, 2007; Kliegl, 2007) presented a comprehensive corpus analysis of single fixation durations as well as gaze durations in a German corpus. Frequency, predictability, and length of the preceding word_{*n-1*}, the fixated word_{*n*}, and the subsequent word_{*n+1*} were reflected in both eye movement measures. In addition, incoming and outgoing saccade amplitude as well as the fixation position within the fixated word_{*n*} (cf., IOVP effect in the next Section 1.3.4) modulated inspection times. The presence of lag, immediacy, and PoF effects suggests that words are typically processed across two or three consecutive fixations (Kliegl et al., 2006). Since lexical processing of parafoveal words has been a contentious issue, it is noteworthy that the PoF effect of word frequency has been reported in German (Kennedy, 1998) and English (Kennedy & Pynte, 2005), while eye movements in a French corpus revealed a sublexical PoF effect of initial trigram informativeness (Pynte & Kennedy, 2006). As a possible explanation, Pynte and Kennedy suggested that differences in average word length mediate the role of semantic PoF effects across languages. As a final remark, the statistical power of corpus analyses makes it possible to simultaneously study the influence of various variables on eye-movement control. Critics, however, have argued that corpus analyses might reflect the influence of uncontrolled variables and that it is impossible to consider all potentially confounding factors. Hence, it has been demanded that effects observed in corpus analyses need to be replicated in controlled experiments (e.g., Drieghe, 2011).

In summary, several words are processed during a single fixation. This is reflected in lag, immediacy, and PoF effects of word length, frequency, and predictability. According to the asymmetry of the perceptual span, lag effects of the preceding word_{*n-1*} arise primarily from internal processes independent of the visual input. Furthermore, gaze-contingent experiments reveal that word length information is extracted from the entire perceptual span, while orthographic and phonologic code is available from the fixated word_{*n*} as well as the next word_{*n+1*}. Furthermore, it is generally accepted that lexical information is available for the preceding word_{*n-1*} and the fixated word_{*n*}; however, lexical processing of the parafoveal word_{*n+1*} remains contentious. Even though this review is far from comprehensive, it provides a general idea about the complexity of processing during a single fixation and outlines current research questions. More information about processing within the perceptual span can be found in several recent reviews (Drieghe, 2011; Hyönä, 2011; Rayner, 2009; Schotter, Angele, & Rayner, 2012).

1.3.4 Oculomotor control

Another important source of eye-movement variability during reading is related to the fixation location within a word. Since words are separated by spaces in Roman scripts, word boundaries are rapidly available in the fovea and parafovea and may subsequently

affect saccade targeting. Within single words, saccades tend to land at the *preferred viewing location* (PVL), located slightly left of the word's center (Rayner, 1979). Saccadic eye movements, however, are far from perfect and cause fixations to vary from the space before a word to the last letter in a word. McConkie, Kerr, Reddix, and Zola (1988) suggested two sources that contribute to the variability in landing sites. First, the *saccadic range error* leads to systematic over- and undershoots of the PVL. If the launch site, that is, the starting point of a saccade, is further away from the PVL than a preferred saccade length, saccades tend to undershoot the PVL. Otherwise, if the launch site is closer to the PVL than a preferred saccade length, saccades tend to overshoot the PVL. Second, *perceptuo-oculomotor variability* generates a random error around the landing site of saccades that increases with saccade amplitude. On top of modulations by launch site and word length, visual layout may affect target selection within a word. Irregular initial letter sequences, for example, cause small shifts of the PVL towards the beginning of words (Hyönä, 1995; White & Liversedge, 2006), while regular initial letter sequences lead to a shift of the PVL towards the word center (Radach, Inhoff, & Heller, 2004).

Variations of fixation positions within a word are the driving force of two other phenomena in reading. First, the probability of refixating a word is at its minimum, when a word is initially fixated at the *optimal viewing position* (OVP; cf., O'Regan, Lévy-Schoen, Pynte, & Brugailière, 1984; O'Regan & Jacobs, 1992). During reading, the OVP is located near the center of a word (McConkie et al., 1989; Nuthmann, Engbert, & Kliegl, 2005; Vitu, O'Regan, & Mittau, 1990; Vitu, McConkie, Kerr, & O'Regan, 2001) and refixation rate increases towards the word boundaries following the shape of a parabola. Second, fixation durations depend on the fixation position within a word. Since both refixation rate and recognition time of isolated words is minimal at the OVP (O'Regan et al., 1984; O'Regan & Jacobs, 1992), the same relation might be expected for fixation durations. Average fixation durations, however, are longest near the word center and decrease towards the word boundaries. Due to its reversed nature, the phenomenon was termed *inverted optimal viewing position* (IOVP) effect (Vitu et al., 2001). As a possible explanation, Vitu et al. (2001) suggested a perceptual economy strategy. Based on prior experience with a task, fixations durations are increased at locations where greater information is anticipated. As an alternative, Nuthmann et al. (2005) proposed that the IOVP effect emerges as a result of mislocated fixations that immediately trigger error-correcting saccade programs (see also Nuthmann, Engbert, & Kliegl, 2007).

The preceding sections illustrate the complexity present in eye movements during reading. Words are fixated once, refixated, or even skipped. Individual fixations range from less than a hundred milliseconds to more than a second. Part of this variability is related to processing of multiple words during a single fixation, which is reflected in lag, immediacy, and PoF effects of word properties (e.g., orthographic, phonological, lexical). But even low-level factors like the fixation position within a word affect spatial and temporal aspects of eye guidance.

1.4 Models of eye movement control

According to Lewandowsky and Farrell (2010), complex phenomena require computational models to be understood and explained. In the case of eye movements during reading, computational models help to deal with this complexity at three levels. First, a large number of independent factors influence eye guidance at a behavioral level (see preceding Section 1.3). While qualitative theoretical accounts often aim to explain a specific effect, consideration of all phenomena and their interactions can rarely be accomplished. In contrast, computational models allow to monitor all effects simultaneously. If necessary, multiple theoretical accounts may even be combined within the same framework and a successful implementation reveals the compatibility of these mechanisms. Second, and related to this, many dependent variables are needed to illustrate target selection and the control of fixation durations at a descriptive level. Again, theoretical consideration of all dependent measures as well as their potential trade-offs seems impossible. Computational models, however, generate a sequence of fixations and saccades, which allows to conduct all analyses of interest within the same data set without limitations introduced by theoretical reasoning. Third, complexity is also given at a neurophysiological level. Reading involves the successful integration of several neuropsychological subsystems. The eyes act both as a perceptive and a motor system. Brain structures collaborate to convert the distorted retinal input into words, retrieve a word's meaning from long term memory, and integrate it into the preceding context. Furthermore, a decision has to be made about when and where to move the eyes, and the next saccade has to be prepared before it is finally executed. Computational models help to consider all processing steps from the uptake of visual information to the execution of a saccade and force to explicitly specify all relevant processing assumptions. At the same time, neurophysiology helps constrain computational models. Visual acuity, for example, decreases from the fovea towards the periphery, a fact that must constrain the area from which visual information is extracted in computational models. The time needed to transmit visual input from the retina to the cortex or by the time needed to prepare a new saccade provide further constraints. Computational models deal with this complexity at all levels simultaneously and thereby help to exceed the limits of theoretical reasoning.

1.4.1 Controversies

During the past decades, several computational models were developed to account for the control of eye movements during reading. While ancestors of current models were either qualitative in nature or focussed on specific aspects of eye guidance, more recent models predict a variety of fixation duration and target selection effects. The development of computational models can be characterized by three major, at least partially overlapping controversies and a corresponding classification of models. Before giving a detailed description of the currently most elaborate computational models, I briefly review these classification systems. The classifications emphasize the most contentious issues of eye movement control during reading and focus on the theoretically most important differences of computational models.

1.4.1.1 Primary oculomotor control vs. cognitive control

Models for the control of eye movements during reading have typically been classified as either oculomotor or cognitive models (Engbert, Longtin, & Kliegl, 2002; Reichle, Rayner, & Pollatsek, 2003; Reilly & O'Regan, 1998; Starr & Rayner, 2001). *Primary oculomotor control* (POC) models assume that eye movements are determined by low level oculomotor factors (and their interactions with basic visual processing), while *cognitive models* emphasize the role of lexical processing. Most importantly, POC models demonstrated that a large fraction of eye movement variability can be explained by low level factors like the visual layout of a text and were supported by the similarity of eye behavior in reading and reading-like tasks (Vitu, O'Regan, Inhoff, & Topolski, 1995). Most POC models, however, focused on either a specific spatial or temporal aspect of eye guidance while more general POC models remained descriptions without computational implementation (e.g., perceptual economy strategy; Vitu et al., 2001).

Spatial control. As described earlier (see Section 1.3.4), words tend to be fixated at the preferred viewing location (PVL) close to a word's center (Rayner, 1979). The variability around the PVL can be described by two sources of errors: A saccadic range error generates systematic over- and undershoots while oculomotor noise adds random deviations around the intended fixation position (McConkie et al., 1988). The mathematical formulation allows a good approximation of fixation positions within words and has been incorporated into several eye movement models (Engbert et al., 2005; McDonald, Carpenter, & Shillcock, 2005; Reichle et al., 1998; Reilly & O'Regan, 1998; Reilly & Radach, 2006). More recently, Engbert and Krügel (2010) proposed a Bayesian approach to account for the systematic variation in saccadic landing sites. The model combines sensory information with a prior distribution of saccade targets to compute the amplitude of the next saccade.

Since the computation of both saccadic range error and oculomotor noise requires the selection of a specific word as the next saccade target, Reilly and O'Regan (1998) computationally explored different target selection mechanisms. According to the *strategy-tactics approach*, saccades move gaze either to the next word or with increasing fixation durations towards the longest word within the upcoming 20 letters. In order to account for modulations of refixation rates within a word (i.e., the OVP effect), all selection mechanisms were supported by an additional process that immediately triggers refixations whenever a fixation position strongly deviates from a word's center (cf., O'Regan, 1990, 1992). In a direct comparison, the strategy-tactics approach outperformed cognitive mechanisms that skip high-frequency words or that are based on sequential attention shifts from one word to the next. Nonetheless, recent eye movement models assume that selection of a target word is at least modulated by cognitive processing (cf., Engbert et al., 2005; McDonald et al., 2005; Reichle, Warren, & McConnell, 2009; Reilly & Radach, 2006) while fixation positions within a word are often based on the oculomotor principles provided by McConkie et al. (1988), namely, the saccadic range error and oculomotor noise.

Temporal control. Minimal control is the most extreme form of a POC model (Suppes, 1990, 1994) and assumes that fixation durations are independent of visual cognitive processing. Even though Suppes (1990, 1994) already acknowledged that such a model fails

to predict the rich eye movement behavior typically observed during reading, minimal control provides a baseline of what can be accounted without consideration of visual processing. The assumption of minimal control was relaxed in the competition/interaction model (Yang & McConkie, 2001; Yang, 2006), where saccades are initiated after random time intervals, but may be inhibited by processing. Depending on the type of processing, inhibition will occur at different points in time. Saccades after short fixations are generally unaffected by processing (less than 150 ms), saccades after fixations of intermediate duration (150 to 200 ms) are prolonged by visual irregularities like missing word boundaries, and only saccades after long fixations (longer than 225 ms) are delayed by lexical processing. Thus, lexical processing may delay the execution of the next saccade, yet only affects a fraction of all fixation durations.

Other POC models focussed on modulations of fixation durations within a word. During reading, fixation durations are longest near the center of a word and decrease towards the spaces between two words (see IOVP in Section 1.3.4). Nuthmann et al. (2005, 2007) explored the potential role of mislocated fixations as a cause of the IOVP effect. According to their hypothesis saccades aim at a specific word. Due to the saccadic range error and oculomotor noise some saccades result in under- or overshoots of the intended target and land on a neighboring word. As a consequence, mislocated fixations immediately trigger corrective saccades. Since the proportion of mislocated fixations is smallest at the word center, fixation durations decrease from the center towards the boundaries. Using mathematical simulations Nuthmann et al. (2007) were able to demonstrate that mislocated fixations might contribute to the generation of the IOVP as well as the OVP effect.

1.4.1.2 Serial vs. parallel processing of words

Even though oculomotor factors contribute to the generation of eye movements, recent computational models agree on the important role of lexical processing for eye guidance. As a consequence, acquisition of lexical information has become the predominant distinctive feature of eye movement models: words are either processed serially or in parallel (Engbert et al., 2002). *Sequential attention shift* (SAS) models assume that lexical processing is limited to single words. Only after successful identification of a word, attention is shifted from one word to the next and due to a tight link between eye movements and attention, cognitive processing is strongly reflected in eye guidance. The principles of SAS models have first been proposed by Morrison (1984) and have subsequently led to a number of different computational models with E-Z Reader (Reichle et al., 1998; Reichle, Warren, & McConnell, 2009) being the most elaborate and prominent implementation.

In contrast, *processing gradient* (PG) models assume that several words are processed simultaneously. The processing gradient in PG models is shaped by visual acuity and allocation of attention. The speed of processing typically depends on the distance of a word from the center of gaze but may change over time due to the reallocation of attentional resources (Engbert & Kliegl, 2011). Mr. Chips (Legge, Klitz, & Tjan, 1997; Klitz, Legge, & Tjan, 2000), an ideal-observer type of model, represents an early implementation of a PG model. In Mr. Chips, processing occurs within a perceptual span and gaze is always directed towards the most informative location. In order to identify the next

saccade target, the model optimally integrates visual, lexical, and oculomotor information. Interestingly, Mr. Chips was able to generate all saccade types by a single target selection mechanism. Model simulations were primarily used to compare optimal performance with performance of normal readers and readers who suffer from a scotoma in the fovea. Contrary to more recent PG models (Engbert et al., 2005; Reilly & Radach, 2006), Mr. Chips neglected the control of fixation durations.

The distinction of serial and parallel processing of words dominated the development of eye movement models during the past decades. Even though a computational implementation of PG models initially seemed complicated and difficult to achieve (Starr & Rayner, 2001), by now several proponents of both model types have been put forward and only few cognitive models remained structurally compatible with both views (McDonald et al., 2005; Feng, 2006).

1.4.1.3 Control of fixation durations

Finally, the third controversy focussed on the mechanisms that control fixation durations. In line with the notion of a just-in-time behavior of the eyes (Ballard et al., 1997), it is often implicitly assumed that gaze is directed towards the most informative region and remains at this location until processed. Even though such an illustration represents a useful first approximation, it is far from obvious how such a strategy is implemented within the oculomotor system. For example, if the decision to move the eyes is postponed until processing of the fixated area is completed, the fovea remains in a “worthless” location during the preparation of the next saccade. In the meantime eccentric locations are processed with reduced acuity for about 150 ms (Becker & Jürgens, 1979). During reading, where average fixation durations last only about 200–250 ms, readers would spend more than half of the time fixating identified words. Hence, a trade-off between processing and saccade initiation is necessary to optimally guide the eyes. Overall, three types of theories have been put forward to describe the potential link between processing and the control of fixation durations: (i) control by a cognitive trigger (direct control), (ii) indirect control, and (iii) mixed control (Rayner & McConkie, 1976; Rayner, 1977; Rayner & Pollatsek, 1981).

Cognitive trigger theories assume a tight link between processing of visual input during a fixation and the decision to move the eyes to a new location. Across tasks, it has been suggested that saccades are triggered by a specific processing event like identification of a word (Morrison, 1984) or estimation of a word’s familiarity during reading (Reichle et al., 1998). According to cognitive trigger theories, fixation durations characterize the time needed to process foveal input. At the same time, cognitive trigger theories need to explain whether, and if so how, saccades are initiated before foveal processing is completed. Otherwise, a large fraction of each fixation will be spent in an already processed location.

Alternatively, *indirect control* theories assume no link between processing of visual input and the decision to move the eyes. Saccades are executed after random time intervals while processing of visual input continues during the preparation of saccades. To account for differences in mean fixation durations across tasks, it is assumed that random timers adapt over time. Adaptation is based on expected processing demands,

either on a trial-by-trial basis (Hooge & Erkelens, 1996) or continuously from fixation to fixation (Hooge, Vlaskamp, & Over, 2007). Contrary to cognitive trigger theories, visual input has no immediate effect on fixation durations and may only affect subsequent fixations. Due to the overwhelming evidence of immediacy effects, current theories for the control of fixation durations during reading abandoned the notion of pure indirect control.

Finally, in *mixed control* theories processing of visual input modulates the decision to move the eyes, but it is not a single specific processing event that triggers saccades. Mixed control mechanisms have been proposed for the control of fixation durations in reading and have led to a diverse set of competing theories. Henderson and Ferreira (1990), for example, suggested that saccade programs are either initiated in synchrony with a shift of attention towards the next word as soon as a word is identified, or after reaching a deadline unrelated to lexical processing (cf., Engbert & Kliegl, 2001). In this case, mixed control represents a combination of a cognitive trigger and an indirect control mechanism. Other models of eye movement control during reading assume that saccades are initiated by random timers. The interval between two saccade initiations, however, may be prolonged by processing of the visual input (Engbert et al., 2005; Feng, 2009; Yang & McConkie, 2001). In this case, mixed control is implemented as the modulation of an indirect control mechanism by ongoing processing.

1.4.2 Computational models

Computational models have often been classified with respect to the aforementioned controversies: (i) oculomotor vs. cognitive control, (ii) serial vs. parallel processing of words, and (iii) the control of fixation durations. By now, the distinction of purely oculomotor and cognitive models is overcome by models that incorporate elements of both aspects to a varying degree. Saccade amplitude is generally computed based on the mathematical formulation given by McConkie et al. (1988) and error correcting saccades are typically considered as potential causes for OVP and IOVP effects (cf., mislocated fixations; Nuthmann et al., 2007). The other controversies, however, remained highly contentious and in particular the distinction of serial vs. parallel processing of words dominated the classification of eye movement models in the past decades. Nonetheless, contrary to computational models in other areas of eye movement research, control of fixation durations has been thoroughly considered during reading. Interestingly, although a distinction of serial and parallel models is in principle theoretically independent of the control of fixation durations, SAS (serial) models have typically been associated with cognitive triggers while PG (parallel) models primarily incorporated indirect or mixed control mechanisms.

1.4.2.1 SAS models and E-Z Reader

Two principles characterize the relation between lexical processing and eye movement control in *sequential attention shift* (SAS) models. First, attention and thus lexical processing is limited to a single word_{*n*}. Only after lexical access of the attended word_{*n*}, attention shifts to the next word_{*n+1*}. Second, both the decision when and where to move the

eyes is linked to attention. In most SAS models programming of the next saccade starts in synchrony with a shift of attention to word_{*n*+1} (Engbert & Kliegl, 2001; Heinzle, Hepp, & Martin, 2010; Morrison, 1984; Salvucci, 2001). Given this assumption and the neurophysiological constraint that saccade programming takes about 150 ms, the eyes spend a considerable amount of time fixating an already identified word. In order to reduce the lag between attention shifts and eye movements, some SAS models initiate the next saccade program before a word is identified (E-Z Reader, Reichle et al., 1998; cf., Engbert & Kliegl, 2001). As a consequence, saccade preparation and processing of the fixated word_{*n*} proceed at least partially in synchrony.

As a major achievement, SAS models provide a single mechanism for the generation of both forward saccades and skippings. According to Morrison (1984), readers execute forward saccades towards the next word_{*n*+1} whenever saccade programming finishes before word_{*n*+1} is identified. Otherwise, if word_{*n*+1} is identified before saccade execution is imminent, the saccade program to word_{*n*+1} is canceled and replaced by a saccade program towards word_{*n*+2}. Thus, even though a skipped word is not fixated, it has been processed in a SAS model. The SAS principles have been explored in a number of computational models. E-Z Reader has been the most influential and systematic implementation (Reichle et al., 1998; Reichle, Warren, & McConnell, 2009). EMMA investigated the SAS mechanism during driving, reading, and arithmetic within the ACT-R framework (Salvucci, 2001). Engbert and Kliegl (2001) relaxed the strict coupling of eye movements and attention by introducing an additional random timing component, and Heinzle et al. (2010) explored the feasibility of SAS principles from a neurophysiological perspective.

In its latest version, E-Z Reader 10 (Reichle, Warren, & McConnell, 2009) consists of preattentive visual processing, allocation of attention, word identification, postlexical integration of words, and oculomotor control. During the preattentive visual processing stage, visual input is acquired in parallel from the entire visual field. While low spatial frequency information is transmitted to the oculomotor system, high spatial frequency information is passed on for subsequent word identification. Lexical processing is limited to single words and proceeds in two stages. During an initial processing stage a word's familiarity is computed. Familiarity represents a rough estimate of a word's processing difficulty and provides the signal to program the next saccade. However, a word's meaning and a corresponding shift of attention is only realized after a second processing stage, that is, lexical access. As a result, processing of word_{*n*} coincides with the preparation of a saccade towards word_{*n*+1} and reduces the temporal lag between shifts of attention and eye movements. In E-Z Reader, lexical processing generally depends on word frequency and predictability with faster identification of high frequent and predictable words. In addition, visual acuity limits recognition of eccentric letters during the initial processing stage, which slows processing of long and distant words. Finally, postlexical integration of word_{*n*} begins immediately after its lexical access, links the identified word into a syntactic structure, generates a context-appropriate semantic representation, and incorporates its meaning into a discourse model. Postlexical integration of word_{*n*} does usually not interfere with lexical processing of word_{*n*+1}, since both processes rely on independent attentional resources. Integration failures, however, shift attention to earlier passages of the text and may be accompanied by regressive eye movements.

All remaining assumptions of E-Z Reader concern oculomotor control. The decision to move the eyes is made after computation of a word's familiarity. Saccade preparation is implemented as a two stage process (cf., Becker & Jürgens, 1979). During an initial labile programming stage, saccade programs may be canceled by the initiation of another saccade program. Cancellation of a saccade program prolongs fixation durations but provides a mechanism to skip subsequent words. During the non-labile programming stage, saccade parameters become fixed and saccade execution is inevitable. If another saccade is initiated during the non-labile programming stage, multiple saccades will be prepared simultaneously and two saccades are executed in close succession. The computation of saccade amplitudes is based on the seminal work of McConkie et al. (1988). Even though saccades generally target at word centers, the actual saccade is modulated by both systematic motor error, which leads to over- and undershoots of the word center, and random motor error, which adds Gaussian noise to the final saccade amplitude. Finally, an additional mechanism generates refixations in E-Z Reader. Since words are identified most quickly when fixated at the center, the probability of refixations depends on the preceding saccadic error and refixations are least likely initiated when a word is fixated at the intended saccade target (i.e., the word center).

E-Z Reader was designed to explore the link between processing and eye movements while taking neurophysiological and behavioral constraints like the eye-brain lag, attention shift delays, and basic oculomotor behavior into account. Over the years, the model has successfully been used to simulate a broad range of eye movement effects during reading (e.g., Reichle et al., 1998; Reichle, Rayner, & Pollatsek, 1999; Reichle et al., 2003; Reichle, Warren, & McConnell, 2009). Due to the close link between lexical processing, attention, and eye movements, E-Z Reader generates immediacy effects of word length, frequency, and predictability. Lag effects of word frequency and predictability arise from the separation of saccade programming and attention shifts, while lag effects of word length result from visual acuity limitations. Furthermore, model simulations generate realistic distributions of fixation positions within words, a saccadic range error with systematic over- and undershoots of the word center, a refixation rate that increases towards the word edges (OVP effect), and regressions due to higher level linguistic processing (clause wrap-up effect, plausibility effect, and garden path sentences). Most problematic for SAS models is the observation of PoF effects, since parafoveal information is only extracted after the identification of the fixated word. Influences of the next word on fixation durations might, however, be explained by mislocated fixations (Drieghe, 2011) or by preattentive processing of the visual layout (Reichle et al., 2003). Until now, the validity of these claims has not been demonstrated in model simulations; in particular, preattentive processing is in its current form underspecified. Overall, E-Z Reader has been very influential for the interpretation of eye movements during reading and has recently been applied to investigate the link between attention shifts and saccade programming in scanning tasks (Reichle, Pollatsek, & Rayner, 2012).

1.4.2.2 PG models and SWIFT

Processing gradient (PG) models provide a natural environment for the generation of lag, immediacy, and PoF effects. All words within the attentional gradient are processed simul-

taneously where the speed of processing depends on visual acuity and the allocation of attention. In general, processing is fastest close to the center of gaze, but processing speed may change over time when attentional resources are released due to the identification of words (Engbert & Kliegl, 2011). Distributed processing poses a serious challenge for the development of computational models since processing of all words and their interaction with eye guidance must be monitored. As a possible solution, the dynamic field theory of movement preparation (Erlhagen & Schöner, 2002) provides a general framework for the control of motor systems. Movement alternatives are represented in a spatially distributed *activation field* where the likelihood of a movement is determined by the relative activation of the corresponding region. The activation field integrates information from various levels (e.g., sensory, memory, movement preparation) and evolves continuously over time. Given the neurophysiological evidence for partial independence of temporal and spatial decisions during the generation of saccades (Findlay & Walker, 1999), this framework guarantees the availability of a saccade target at any point in time (Engbert & Kliegl, 2011).

The two most elaborated PG models, Glenmore (Reilly & Radach, 2006) and SWIFT (Engbert et al., 2005), make use of a dynamic activation field.² As a major achievement, all saccade types observed during reading (i.e. forward saccades, skippings, refixations, and regressions) can be explained by a single principle related to distributed processing (cf., Mr. Chips; Legge et al., 1997). Saccade targets are selected from a continuously evolving activation field, shaped by the simultaneous sensory and linguistic processing of multiple words. While both models share a number of similarities, the major difference between Glenmore and SWIFT is related to linguistic processing. Word identification is more specific in Glenmore and considers processing both at the level of letters and words. In contrast, SWIFT is more elaborate, when it comes to saccade programming and low-level oculomotor control, and currently reproduces a broader range of eye-movement phenomena during reading. Since this thesis intends to explore principles of eye guidance during reading in non-reading tasks, basic oculomotor control as well as a broader general scope seemed to be more important than detailed assumptions about linguistic processing. Therefore, to give an example of a PG model, I provide a detailed description of SWIFT.

In SWIFT (Engbert et al., 2005), words serve as units of an one-dimensional activation field. The activation of each word changes over time due to word recognition. During an initial preprocessing stage, activations rise to a maximum before they start to decline during a second lexical completion stage. Word difficulty, measured by the frequency of occurrence in printed text, determines the maximum activation. Because of distributed processing, activations of several words within an processing gradient evolve simultaneously. The lexical processing rate (i.e., speed of processing) of each word is limited by visual acuity, which is a function of distance from the center of gaze. In general, processing proceeds faster for words close to the center of the visual field. Two additional factors affect the final lexical processing rate: (i) due to an asymmetry of the perceptual span, the processing gradient in SWIFT extends further to the right (i.e., in the direction of reading) and (ii) predictability of a word modulates processing speed of foveal and parafoveal words.

²A saliency map adopts the function of an activation field in Glenmore (Reilly & Radach, 2006).

The activation field in SWIFT can be interpreted as a saliency map (e.g., Findlay & Walker, 1999), which is used to compute the target of the next saccade. Before processing, a word is unknown, and it is recognized when processing is completed. In both cases activations are minimal (i.e., zero) and will not attract gaze. The remaining words (i.e., with non-zero activations) compete as the next saccade target. Target selection is a stochastic process and the probability to select a word as the next target depends on its relative lexical activation. Motivated by neurophysiological findings, SWIFT explicitly assumes a separation of temporal and spatial control of eye movements (Findlay & Walker, 1999). Thus, the decision when to move does not depend on the decision where to move gaze. An autonomous timer controls fixation durations, initiating saccades after random time intervals. This stochastic process generally works in isolation of lexical processing, but may be inhibited by processing of the fixated word (i.e., foveal inhibition). Due to the time needed for lexical processing, foveal inhibition affects saccade timing with a temporal delay. Consequently, foveal inhibition may affect both the current as well as the next fixation duration and contributes to the generation of immediacy and lag effects. Additional processing time may also be gained by programming a re-fixation and is not restricted to timer modulations by foveal inhibition.

The remaining assumptions of SWIFT concern oculomotor control and share a lot of similarities with other eye movement models. Saccade programming is implemented as a two-stage process consisting of a labile and a non-labile saccade program (cf., Becker & Jürgens, 1979). The model can cancel saccade programs during the labile programming stage and selects the next target from the activation field only after the transition from the labile to the non-labile saccade programming stage. The realized saccade amplitude is determined by the chosen word, a systematic and a random motor error (McConkie et al., 1988). Thus, like E-Z Reader, SWIFT considers systematic shifts of within-word fixation position distributions depending on the launch site of the preceding saccade. If saccades are misguided and land unintendedly on a neighboring word (i.e., a mislocated fixation, Nuthmann et al., 2005), SWIFT initiates a new saccade immediately, to compensate for the saccadic error. However, even after mislocated fixations target selection is based on the dynamics within the activation field and will not lead to a re-fixation in every case. Finally, programming of small saccades is more time consuming. Since target selection occurs at the transition from the labile to the non-labile stage, durations of the non-labile programming stage are prolonged during the preparation of short saccade amplitudes. This mechanism contributes both to the generation of IOVP and successor effects.

In its current form (Engbert et al., 2005) SWIFT generates realistic eye movement patterns at the level of target selection³ and the control of fixation durations.⁴ Most effects cannot be assigned to a single control principle, but arise from the dynamics of the activation field and their interaction with the mechanisms of target selection and saccade timing. Due to differential temporal evolutions of activations, foveal inhibition is a major source for the successful simulation of immediacy and lag effects of word length, frequency, and predictability, while simultaneously maintaining the variability observed

³The evaluation was based on the probability of two fixations, three and more fixations, word skipping, and regressions.

⁴The evaluation was based on first fixation duration, second fixation duration, single fixation duration, gaze duration, and total reading time.

in fixation duration measures. Exploratory analyses revealed that the dynamics of the model even generate successor (PoF) effects of the next word (Engbert et al., 2005). These effects, however, are rather small and a comparison with experimentally observed PoF effects should be performed in future simulations. At a low oculomotor level, SWIFT tends to fixate words at their center (cf., PVL; Rayner, 1979) and systematically shifts the distribution of fixation positions with the preceding launch site (cf., McConkie et al., 1988). In addition, model simulations capture the modulation of refixation rate (cf., OVP effect; McConkie et al., 1989) as well as the modulation of fixation durations within words (cf., IOVP effect; Vitu et al., 2001). Finally, subsequent model simulations provided a potential explanation for the generation of skipping costs and skipping benefits during reading (Engbert & Kliegl, 2011). The results, however, have only been achieved in isolation without reanalyzing other phenomena like immediacy or lag effects. In summary, SWIFT (Engbert et al., 2002) was among the first models to show that it is possible to implement the principles of distributed processing within the framework of a computational model that accounts for both spatial and temporal aspects of eye-movement control during reading. Because of its architecture and the broad range of phenomena captured in model simulations, SWIFT provides a promising candidate to explore eye guidance from the perspective of a PG model in non-reading tasks.

1.5 Present studies

Among the paradigms that require a fixation-saccade strategy, reading belongs to the most extensively investigated tasks. Several characteristics facilitate the simultaneous investigation of spatial and temporal aspects of eye movement control and contribute to the great progress made in reading research. First, reading is a well-defined task. In order to understand a text in alphabetic scripts like German or English, a sequence of fixations moves the eyes from left-to-right. Contrary to most other tasks, this limits the number of potential saccade targets considerably, which helps understand the dynamics of target selection. Second, words are non-overlapping objects, separated by spaces in most modern scripts. Hence, fixations can be unambiguously assigned to a specific word in order to investigate influences of the fixated and neighboring words. Third, text material varies at several levels (e.g., phonological, orthographic, lexical, syntactic, semantic) and provides insights into the complexity of processing. Contrary to other tasks, where processing demands are often unknown, psycholinguistic knowledge helps to systematically modify these factors. Word length, predictability, and frequency, for instance, control word difficulty (the time needed to recognize a word). Finally, by asking comprehension questions after a text has been read, it can be ensured that participants perform a task without disturbing its performance. While the investigation of eye movements during reading has been very fruitful and led to the development of a number of elaborate computational models, it remains unclear, how the control of eye movements during reading relates to eye movements in non-reading tasks.

In order to examine eye movement control in non-reading tasks, we designed two scanning/search paradigms inspired by work from Hooge and Erkelens (1998). We used Landolt-'C's as stimuli in all experiments but tried to take advantage of the characteris-

tics inherent to reading. The stimuli allowed to systematically manipulate processing demands by modulating gap size, contrast, or line-width, while avoiding potential confounds of other variables like orthography and syntax. Task design limited the number of potential saccade targets and guaranteed the spatial separation of stimuli, so that each fixation could be assigned to a specific symbol. Thematically, the three main controversies about eye movement control during reading served as the basis of our investigations. Our work aimed to see whether principles of eye movement control during reading generalize to non-reading tasks and in turn whether eye movements in non-reading tasks might contribute to the solution of ongoing controversies of eye movement control during reading. Chapter 2 deals with the role of low-level oculomotor control in non-reading tasks (see also Chapter 4), Chapter 3 centers on serial vs. parallel processing, and Chapter 4 focuses on the control of fixation durations.

1.5.1 Oculomotor control in a sequential search task

Fixation position within a word is among the most crucial factors of eye-movement control during reading and influences fixation durations on a word, the next saccade target, and the subsequent fixation position within a word. The existence of fixation position effects were demonstrated in a number of tasks using text or text-like stimuli (Vitu et al., 1995; Vitu, Lancelin, & Marrier d'Unienville, 2007) and strengthened the idea that eye-movements during reading are basically controlled by low-level oculomotor strategies (e.g., O'Regan, 1992). More recent theories emphasize the relevance of high-level cognition like lexical processing, but low-level oculomotor control remains an important source of eye movement variability and is taken into account in existing computational models (Engbert et al., 2005; Reichle, Warren, & McConnell, 2009).

Until now, analyses of within-object fixation positions have primarily been applied to tasks using words or word-like stimuli. Since word identification depends on the recognition of fine details (letters), effects of fixation positions may have been acquired as an optimal strategy to process words. In contrast, if fixating objects at the center provides a processing advantage, fixation position effects may be a general principle of eye movement control. In that case, fixation position effects should be observed across tasks and stimuli.

In Chapter 2, we examined effects of the fixation position within an object in a sequential search task. The task required a series of eye movements along a path hidden in a complex display of Landolt-'C's (Fig. 2.2). Participants fixated stimulus elements in a sequential order, since gaps of the fixated stimulus revealed the position of the next stimulus. Rayner (1979) reported that readers preferred to fixate words close to their center at the preferred viewing location (PVL). We observed a similar preference in our task. Fixation positions distributed approximately normally around the horizontal and vertical center of Landolt-'C's. As suggested by McConkie et al. (1988) for eye movements during reading, subsequent analyses confirmed that two factors contribute to the variability in fixation positions around the PVL. First, a saccadic range error led to systematic over- and undershoots. Saccades tended to overshoot, if the PVL of the next saccade target was closer than a preferred saccade length. On the contrary, saccades tended to undershoot if the PVL of the next saccade target was further away than a

preferred saccade length. Second, perceptuo-oculomotor (or sensorimotor) noise added additional variability to the landing site distributions.

At least two other phenomena originate from variability of fixation positions within words. McConkie et al. (1989) reported an optimal viewing position (OVP) during reading, where the probability of refixating a word was minimal. The OVP is located close to the center of words and follows a U-shaped function. In the sequential search task, refixation rate was modulated by fixation positions. We replicated a quadratic curve of refixation rates around the symbol center for deviations perpendicular to the movement direction indicated by the task. However, refixation rate decreased linearly with decreasing distance towards the next stimulus. Furthermore, in reading, fixation durations on a word depend on the fixation position within a word. Fixation durations are longest near the center of a word and decrease towards a word's boundaries (IOVP Vitu et al., 2001). In our task, fixation durations depended on horizontal and vertical fixation position and were longest near the gap of a Landolt-'C'. Interestingly, the IOVP effect was much stronger than expected from previous results obtained during reading.

In summary, the experiment described in Chapter 2 was among the first to investigate the influence of horizontal and vertical fixation positions within an object on subsequent eye movements in a non-reading task. Fixation positions affect eye guidance at several levels. While saccades are generally directed towards the center of an object, deviations from a preferred saccade length lead to systematic shifts of the fixation position. Furthermore, fixation positions affect target selection so that refixation rate increases with increasing distance to the center. Finally, fixation durations were longest close to the gap and decreased with increasing distance.

1.5.2 Distributed processing of objects

In Chapter 3, we tested specific predictions of a class of models initially developed to account for eye movements during reading. SAS models postulate that allocation of attention is restricted by serial processing of objects/words. Even though developed for reading, the framework has recently been applied to scanning tasks and has become an heuristic tool for the interpretation of eye movements (Reichle et al., 2012). In Chapter 3, we test three predictions of SAS models with the sequential scanning task introduced in the preceding study.

First, SAS models predict no effect of upcoming stimulus elements on fixation durations. Our analyses, however, reveal strong modulations of fixation durations by the next stimulus $n + 1$, that is, a parafoveal-on-foveal (PoF) effect. PoF effects have previously been interpreted as evidence for distributed processing (Kennedy, 1998, 2000). Proponents of SAS models, however, suggested that PoF effects are caused by saccadic undershoots. While the eyes fixate the preceding word, attention is already allocated on the next word (Drieghe, 2008). To disentangle these accounts, we investigated fixation durations before refixations, since in SAS theories, both the decision to refixate and refixations resulting from saccadic undershoots are based on the fixated object. Using this conservative test for PoF effects, we observe fixation duration modulations by the next item before refixations. Thus, our results cannot be explained by saccadic undershoots in SAS models and provide

support for distributed processing. Interestingly, subsequent stimuli had no effect on fixation durations.

Second, modulations of fixation durations by stimulus elements far from the actual saccade target contradict SAS models, where the attentional shift operation restricts target selection to stimulus elements close to the next saccade target. We evaluated the probabilities of forward saccades, skippings, and refixations as a function of distance from the fixated stimulus to the next direction change. Probabilities of saccade types were reliably affected by distant stimulus elements. The probability of a forward saccade from stimulus n to stimulus $n + 1$, for example, was modulated by direction changes up to six stimulus elements away ($n + 6$). All analyses controlled for potential confounds of priming or other characteristics of the path.

Third, skipping of stimulus $n + 1$ by making a saccade straight from stimulus n to stimulus $n + 2$ induces prolonged fixation durations in SAS models. Skipping costs arise from the cancellation of a saccade program to the next stimulus $n + 1$ and the initiation of a new saccade program to stimulus $n + 2$. Contrary to the predicted skipping costs, we observed skipping benefits, that is, a reduction of fixation durations before skippings. Skipping benefits persisted across movement directions and were not compensated on the preceding or succeeding fixation.

Our results contradict several predictions of SAS models. Even though sequential attention shifts might represent a useful approximation of eye-movement control in some tasks, a closer inspection reveals that SAS models cannot account for the complexity of behavior observed in scanning tasks. Instead, our results support parallel processing of multiple items in this type of scanning task. Model generalizability is a key concept for the evaluation of computational models (Pitt, Myung, & Zhang, 2002). Since, parallel models have also been proposed for the control of eye movements during reading, an architecture that is based on spatially distributed processing may underly the control of eye movement across tasks.

1.5.3 ICAT: A computational model for the control of fixation durations

In Chapter 4, we focus on the control of fixation durations in saccadic sequences. We review the literature on reading, visual search, scene perception, and scanning tasks. Three classes of theories have been proposed to account for fixation durations: (i) control by a cognitive trigger, (ii) indirect control, and (iii) mixed control. Even though experiments lead to seemingly incompatible interpretations, fixation duration patterns can be described by a form of mixed (asymmetric) control (Hooge et al., 2007) across tasks. While ongoing processing may prolong fixation durations immediately, reductions of fixation durations are time consuming and will only show up on later fixations. We propose that the asymmetry in the control of fixation durations originates at two different levels: (i) *local control* relies on processing of the fixated item and modulates the current fixation while (ii) *global control* depends on overall task requirements and affects fixations over sustained periods (not just the current fixation). Cognitive trigger theories and mixed control models provide detailed accounts for local control. Global control, however, is

either neglected or only implicitly assumed in recent theories, even though it represents a key component of indirect control (Hooge & Erkelens, 1998).

Based on our conclusions, we present three principles that may underlie asymmetric control. First, the prime mechanism driving eye movements is an indirect control mechanism. Second, the indirect control mechanism may be modulated by ongoing processing (i.e., local control). Third, indirect control adapts over time. Adaptation, however, is a slow process and will only affect later fixations (i.e., global control). Starting from these principles, we built a fully implemented computational model: ICAT.⁵ An *autonomous timer* serves as the indirect control mechanism that initiates saccades after random time intervals. If processing is highly demanding, *foveal inhibition* may prolong fixation durations. Otherwise, the random duration remains unchanged. The *adaptation of saccade timing* depends on expected processing demands. Both the autonomous timer and foveal inhibition adapt from fixation to fixation. If processing during the next fixation is expected to be highly demanding, the autonomous timer generates long time intervals and foveal inhibition has no effect on fixation durations. However, if processing is expected to be easy, the autonomous timer will on average generate a short time interval. In addition, foveal inhibition will prolong fixations whenever processing demands are higher than expected.

Although implicitly assumed, adaptation of saccade timing (i.e., global control) has been neglected in indirect control theories. In ICAT we explicitly incorporate these adjustments at the level of the autonomous saccade timer and at the level of foveal inhibition. Via single trial simulations, we illustrate the temporal evolution of our model. Furthermore, we explicitly investigate the functional role of both adjustments by systematically deactivating the processes. Our simulations demonstrate the necessity of both adaptive processes to generate asymmetric control of fixation durations.

In the second part of Chapter 4, we evaluate the main assumptions of ICAT. In two search tasks, participants looked for a closed ring within an array of Landolt-'C's. In half of all trials, we introduced a stepwise change in processing demands by varying target-distractor similarity (gap size of distractors). In both experiments, our results confirm the notion of asymmetric control. Fixation durations immediately lengthen, when processing demands increase, and decrease with a temporal delay, when processing demands decrease.

Incorporating ICAT into a full model of eye movement control (SWIFT; Engbert et al., 2005), we demonstrate that model simulations reproduce the complex spatio-temporal patterns observed in the eye movements. The full model meets the assumptions about eye guidance outlined in the discussion of Chapter 3 and replicates mean fixation durations and fixation duration distributions that we observed in these experiments. In addition, our model generates effects of fixation positions within an object (see Chapter 2) as well as skipping benefits (see Chapter 3).

⁵Inhibitory Control with Adaptive Timer

Chapter 2

Oculomotor control in a sequential search task

Hans A. Trukenbrod and Ralf Engbert
University of Potsdam, Germany

Running Head: Oculomotor control

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Abstract

Using a serial search paradigm, we observed several effects of within-object fixation position on spatial and temporal control of eye movements: the preferred viewing location, launch site effect, the optimal viewing position, and the inverted optimal viewing position of fixation duration. While these effects were first identified by eye-movement studies in reading, our approach permits an analysis of the functional relationships between the effects in a different paradigm. Our results demonstrate that the fixation position is an important predictor of the subsequent saccade by influencing both fixation duration and the selection of the next saccade target.

2.1 Introduction

The analysis of eye movements is among the best measures of visual information processing in visual search, reading, or general scene perception (Rayner, 1998; Findlay & Gilchrist, 2003). First, eye movements provide an online measure of processing, because of the fast sampling rate of about 3 to 5 fixations per second, i.e., average fixation durations are between 200 and 300 ms (Rayner, 1998). Second, it is well-established that absolute search times depend on the number of fixations during a trial (Luria & Strauss, 1975; D. E. Williams, Reingold, Moscovitch, & Behrmann, 1997). Third, there is a tight coupling between attention and saccadic eye movements: While it is possible to generate covert shifts of attention without eye movements, both voluntary eye movements (Deubel & Schneider, 1996; Kowler et al., 1995; Hoffmann & Subramaniam, 1995) and involuntary eye movements (Peterson, Kramer, & Irwin, 2004) are generically preceded by shifts of attention towards the saccade target location. Moreover, miniature (or “fixational”) eye movements are related to covert shifts of attention (Engbert & Kliegl, 2003a; Laubrock, Engbert, & Kliegl, 2005; for an overview see Engbert, 2006). Therefore, studies of eye movements enable us to reconstruct the time-course of attention allocation in general perception.

Inherent stochasticity, however, is an important component of saccadic eye movements: First, saccadic scanpaths are complex random-walks with long-range correlations (Brockmann & Geisel, 2000; Engbert, Kliegl, & Longtin, 2004). Second, fixation durations and fixation locations within visual items show considerable variability from fixation to fixation.¹ As a consequence, theoretical models of saccade generation are strongly influenced by several sources of noise. For example, the SWIFT model for reading eye movements is driven by probabilistic target selection, stochastic processes of diffusion-type for the control of fixation durations, and oculomotor errors (Engbert et al., 2002, 2005). Interestingly, using a theoretical model, we have shown that noise can improve performance in the case of reading (Engbert & Kliegl, 2003b).

Here, we focus on variability in fixation locations within search-items in a sequential search task. From research in reading, it was observed that a considerable amount of the variability in measures of visual information processing is related to fixation positions within a word (e.g., Rayner, 1979; McConkie et al., 1988; Vitu et al., 1990, 2001; Nuthmann et al., 2005). We were interested whether these experimental findings transfer to visual search paradigms. As a first attempt, we developed a sequential search task motivated from earlier work by Hooge and Erkelens (1998). The sequential nature of our task was intended to facilitate the comparison to eye movements in reading.

2.1.1 Eye movements during visual search

Visual search, i.e., looking for a specific object in a visual display, is a central task of everyday visual activity. Following Findlay and Gilchrist (2003, p. 105), “a great deal of research and theory within visual search has ignored eye movements altogether.” Therefore, it is not surprising that the impact of landing positions within search-items on

¹A third source of stochasticity is related to miniature eye movements generated during fixation (e.g., Engbert & Kliegl, 2004; Mergenthaler & Engbert, 2007).

subsequent eye-movement behavior has hardly been investigated (but see, e.g., Henderson, 1993).

In simple search tasks, i.e., feature or parallel search (Treisman & Gelade, 1980; Wolfe, 2003) only a single or sometimes no eye movement is required to identify the target. As a consequence, saccadic scanpaths are trivial, because single fixations are typically observed, and, hence, it is precluded by the task to explore dynamics of fixation position on subsequent eye-movement behavior. Nevertheless, studies of eye movements in simple search paradigms yielded important information about target selection, demonstrating that the eyes generally fixate near or even on a symbol (Findlay, 1995, 1997) and that the landing sites are shifted and are more variable if the target is presented simultaneously with a second target or with distractors; a phenomenon related to the *global effect* (Findlay, 1982).

In more difficult search tasks, i.e., conjunction or serial search (Treisman & Gelade, 1980; Wolfe, 2003), sequences of saccades have been studied (L. G. Williams, 1967; Luria & Strauss, 1975; Hooge & Erkelens, 1996, 1998, 1999; Motter & Belky, 1998a, 1998b; Zelinsky, 1996; Zelinsky & Sheinberg, 1997). Most importantly, it has been shown that saccades are selectively directed towards symbols similar to the target in color, shape, or size (L. G. Williams, 1967; Luria & Strauss, 1975; Zelinsky, 1996; Findlay, 1997; Motter & Belky, 1998b), providing further evidence that eye movements can be examined to study covert shifts of attention. Differences in selectivity were contingent on differences in fixation duration (Hooge & Erkelens, 1999). Saccades are more likely directed to a symbol similar to the target if the previous fixation duration increases.

Spatio-temporal dynamics of eye movements have also been studied in more complex scenes (pictures of objects or natural scenes) or during everyday activities. The gaze during real-world scene perception is controlled by two major factors (Henderson, 2003). First, because of stimulus-based gaze control, properties of the image such as spatial frequency of contrast, color, edges, and luminance affect the distribution of fixations across a scene (Mannan, Ruddock, & Wooding, 1997; Reinagel & Zador, 1999; Parkhurst & Niebur, 2003; Tatler, Baddeley, & Gilchrist, 2005; Tatler, Baddeley, & Vincent, 2006). These properties, however, vary at a given fixation position with the preceding saccade length (Tatler et al., 2006). Second, knowledge-driven gaze control affects characteristics of eye movements. The eyes do not necessarily fixate at a point that is the most visually salient (M. Hayhoe & Ballard, 2005). Instead, saccades aim at interesting or informative regions in a scene (Buswell, 1935; Yarbus, 1967; Loftus & Mackworth, 1978) and differ considerably across well-learned activities such as reading (Rayner, 1998), driving (Land & Lee, 1994), different kinds of sport (Land & Furneaux, 1997; Land & McLeod, 2000), and while making tea or a sandwich (Land & Hayhoe, 2001). Furthermore, distributions of fixation positions in a given scene differ when searching for a target object compared with the corresponding measures when trying to memorize that scene. In general, context of a scene is used to guide eye movements. The gaze remains fixated longer on semantically informative objects and fixates them more often (Henderson, Weeks, & Hollingworth, 1999).

Only a few studies investigated the influence of fixation location on saccade sequences. One example is the work of Vergilino-Perez and Findlay (2006) demonstrating differential effects of first landing site on second landing site for within-object and between-object

saccades. Saccades from the first fixation position did not differ in amplitude for various landing sites if saccades were directed to the same symbol. Within-object saccades were not modulated by within-object fixation location. Thus, Vergilino et al. concluded that refixations were preprogrammed. In contrast, average amplitude of between-object saccades was influenced by the first fixation position. Vergilino-Perez and Findlay (2006) replicated this behavior for horizontal, oblique and vertical eye movements in both the left and right direction. In another study concerned with the impact of fixation position on subsequent eye movements, Findlay, Brown, and Gilchrist (2001) reported a higher rate of very brief fixation durations (less than 90 ms) when the eyes fixated a blank space between two symbols compared to fixations on a symbol or near a symbol (within 0.5° of edge).

In general, it is assumed that fixation durations represent the amount of foveal processing during visual search, resulting in longer fixations when fixated stimuli are more complex (Gould & Dill, 1969) or harder to discriminate from a target (Hooge & Erkelens, 1998). Contrary to foveal stimuli, peripheral stimuli did not affect fixation durations during visual search (Hooge & Erkelens, 1999). Fixation durations, however, are not entirely adjusted to task demands. For example, single fixations on a target symbol are often not sufficient to terminate the search process and to prevent subsequent saccades to other non-targets (Gould, 1973; Hooge & Erkelens, 1996). Hooge and Erkelens (1998) concluded that mean fixation duration is determined by the average processing time of several previously fixated symbols. Thus, different from a direct control process, saccades are initiated after an estimated time interval.²

2.1.2 Oculomotor control during reading

For saccade generation in reading, a number of publications analyzed the relation between within-word fixation position and subsequent eye movements. In general, eyes initially tend to fixate at the *preferred viewing location* (PVL; Rayner, 1979). Even though saccades seem to target at or slightly left of the word center, i.e., the PVL, the actual landing site varies considerably between different fixations from the first to the last letter of a word. The variation in landing sites leads to an approximately Gaussian distribution around the PVL (Fig. 2.1a). McConkie et al. (1988) confirmed the existence of the PVL at or slightly left of the word center for words with 4 or more letters. More importantly, McConkie et al. demonstrated that the PVL did not just depend on word length, but was additionally modulated by the launch site of saccades. It turned out that the PVL and its landing site distribution is a composite distribution of several landing site distributions generated by saccades with different launch sites. Following McConkie et al. (1988), we can define the *launch site distance* as the distance of the previous fixation position (the launch site) from the PVL of the next target word (landing site). Landing site distributions are shifted to the left of the PVL for far launch sites and to the right for launch sites close to the target word. Thus, there is a systematic relationship between launch site distance and landing site, which was theoretically explained by the *saccadic range error* (McConkie et

²In reading, we proposed that the timing of saccades is controlled by a similar estimation process (Engbert et al., 2005). Moreover, there is evidence for distributed processing over several words at a time (Kliegl et al., 2006; see Reichle et al., 2003, for a discussion of alternative views).

al., 1988). Additional random errors due to perceptuo-oculomotor noise produce the observed broad normal distributions of within-word fixation positions. In addition to modulations of the PVL by launch site and word length, the exact position of the PVL depends on other word properties. For example, irregular initial letter sequences lead to small shifts of the PVL towards the beginning of words (Hyönä, 1995; White & Liversedge, 2006).

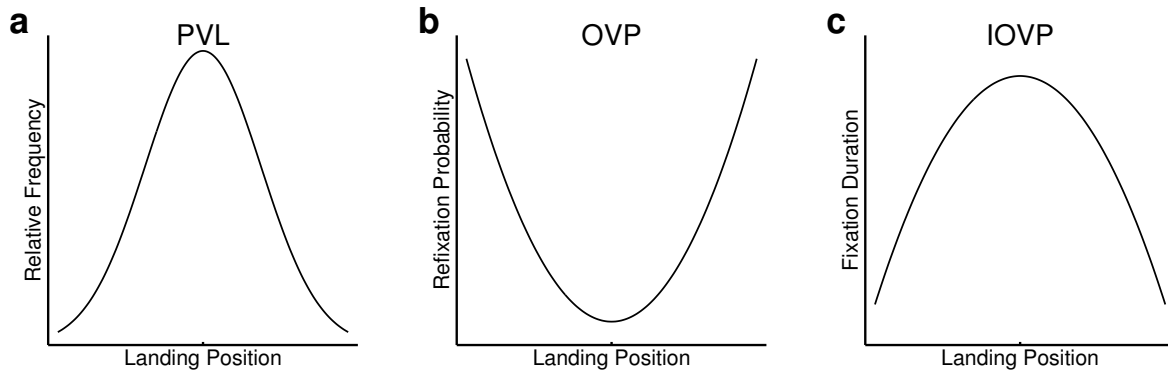


Figure 2.1: Schematic illustration of basic oculomotor phenomena in reading. (a) The preferred viewing location (PVL) is the local maximum of the distribution of within-word fixation positions. (b) The optimal viewing position (OVP) can be read off from the minimum of the probability of generating a refixation. (c) The inverted optimal viewing position (IOVP) effect for fixation durations is given by the fact that fixation durations are shorter near word edges compared to the word center.

The variability of within-word fixation position is a driving force of two other effects observed in reading. First, McConkie et al. (1989) investigated eye movements following the initial fixation of a word and reported an *optimal viewing position* (OVP) slightly right of the word center: When the first fixation is located at the OVP the probability of an immediately following refixation, i.e., a secondary saccade producing a within-word shift of the fixation position, is at its minimum. Refixation probability increases towards the word boundaries (Fig. 2.1b). Vitu et al. (1990, 2001) and Nuthmann et al. (2005) reproduced the OVP effect during reading. These later studies, however, showed that the OVP was shifted to the left and matched the PVL slightly left of the word center.

Second, Vitu et al. (2001) discovered surprising differences in fixation durations depending on within-word fixation positions. The fact that refixation probability is close to its minimum at the word center suggests that the word center represents the optimal fixation position for word identification. Therefore, we can expect that fixation durations display a minimum at the OVP. Counter to this expectation, however, Vitu et al. (2001) observed that fixation durations are highest near the word center and decrease towards word edges (Fig. 2.1c). Consequently, this effect was termed the (*fixation-duration*) *inverted optimal viewing position* (IOVP) effect. As a possible explanation Vitu et al. (2001) suggested a *perceptual economy strategy*. Based on prior experience, fixations durations are increased at locations where greater information is anticipated. Recently, Nuthmann et al. (2005) proposed that the IOVP effect emerges as a result of mislocated fixations that trigger immediate error-correcting saccade programs (see also Nuthmann et al., 2007; Engbert, Nuthmann, & Kliegl, 2007).

2.1.3 Oculomotor control in other tasks

Oculomotor effects were studied in few tasks other than reading and visual search. First, Vitu et al. (1995) investigated eye movements during scanning of z-strings. For comparisons with eye movements in reading, all letters were transformed into 'z' or 'Z' letters (see also Nuthmann et al., 2007). Vitu et al. reported similar distributions of landing positions as well as refixation probabilities in z-string scanning and reading. Furthermore, even during search for the letter 'c', eye-movement behavior closely matched eye movements during reading. From these observations, Vitu et al. (1995) concluded that a predetermined oculomotor scanning strategy might be essential to guide eye movements during reading. Rayner and Fischer (1996) observed similar landing sites distributions during reading and scanning of z-letter strings, but they did not find a PVL during the search task of a target word. The OVP effect, i.e., the fact that the refixation probability is lowest in the center of a word, was not replicated during z-string scanning, but the probability of a single fixation exhibited a maximum, if the words or letter strings were fixated near the center in all conditions.

Second, Henderson (1993) recorded eye movements while participants viewed arrays of line drawings of different objects. The initial landing position was normally distributed and centered around the middle of the object. Furthermore, refixation probability increased (OVP) while first fixation duration decreased (IOVP) as the deviation of the initial landing position from the object center increased. Even though participants made both horizontal and vertical eye movements, PVL, OVP, and IOVP curves during object processing were averaged over both movement directions. Thus, it is unclear whether effects were equally pronounced for both horizontal and vertical landing sites.

2.1.4 Present study

The aim of the present study was to compare oculomotor behavior in reading and visual search. More specifically, we investigated whether oculomotor phenomena observed in reading research transfer to other tasks. Our task is a sequential variant of a task used by Hooze and Erkelens (1998). In the original task, all symbols pointed into the direction of the target symbol. To facilitate a comparison with eye movements during reading, we developed a search task which required sequential movements along a pre-determined search path hidden in a complex display. We analyzed (i) the effect of the preferred viewing location, (ii) launch-site effects on the distributions of landing positions, (iii) the existence of an optimal viewing position, and, finally, (iv) the inverted optimal viewing position effect for fixation durations.

2.2 Method

2.2.1 Participants

Our 23 participants, all students of the University of Potsdam, were aged between 19 and 28 years. All participants reported normal or corrected-to-normal vision and received study credit or were paid 5€.

2.2.2 Task and stimuli

Participants were required to find a closed circle by analyzing a sequence of stimulus elements indicating the search direction. Each stimulus was a Landolt 'C', where the gap pointed towards the next stimulus item. Gap positions of symbols outside the search path were randomly chosen. Gray stimulus items were presented on a bright gray background. Figure 2.2a shows a typical search display used in the experiment (in the figure, the start item is highlighted in bold font). The gap on the left side of the start item indicated a movement direction to the left. Next, the gap at the top of the item requires an upward saccade. The sequence extends to the target symbol, a ring without gap (a closed circle).

Displays consisted of 196 Landolt 'C's in a tetragonal arrangement with 14 rows and 14 columns, respectively. The distance between the centers of horizontal or vertical adjacent stimulus elements was 2.33° . All participants viewed the same paths, where path lengths ranged from 51 to 60 symbols. Each Landolt 'C' stimulus had a diameter of 0.78° and a ring's line width was 0.08° . Gap sizes of all 'C' stimuli in each display were randomly chosen from the set of three different sizes, 0.04° , 0.12° , or 0.20° .

At the beginning of each trial, participants were asked to fixate a white 'C' which was presented in isolation to preclude coincidental preview of parts of the search display or the target symbol. After successful fixation, the complete display appeared and participants were required to process the sequence of symbols and to find the circle. Participants were instructed to fixate the target as soon as it was identified and to press a key to terminate a trial. Each participant performed 50 trials.

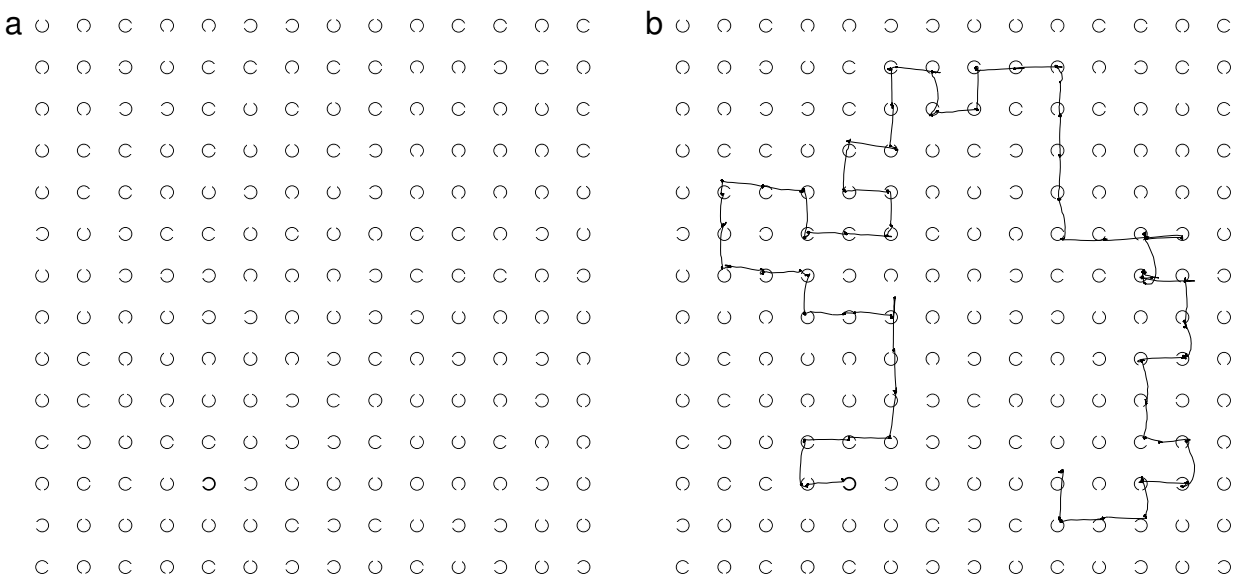


Figure 2.2: Sequential search task. (a) Participants were instructed to follow a path given by a sequence of Landolt 'C's, where the opening of each stimulus element in a sequence gives the movement direction to the next symbol. The starting symbol is marked with bold font, while the target symbol is a closed circle. (b) A typical eye-movement trajectory generated by a participant.

2.2.3 Eye movement recording and stimulus presentation

The experiment was presented on a 19-in. EYE-Q 650 CRT monitor (1024×768 resolution; refresh rate 100 Hz) controlled by an Apple Power Macintosh G3 computer. Eye move-

ments were recorded using the video-based Eyelink-II System (SR Research, Osgoode, ON, Canada) with a sampling rate of 500 Hz and an instrumental spatial resolution of less than 0.01° . Participants' head movements were reduced by using a chin rest. The experimental software controlling stimulus display and response collection was implemented in MATLAB (The MathWorks, Natick, MA, USA), using the Psychophysics (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen, Peters, & Palmer, 2002) toolboxes.

2.2.4 Data preprocessing

To reduce noise in the mapping from eye positions to stimulus items, we averaged time-series of eye positions of both eyes. Saccades were detected using a velocity-based algorithm proposed by Engbert and Kliegl (2003a) and recently updated by Engbert and Mergenthaler (2006). For each fixation a mean fixation position was computed and assigned to the closest symbol. Fixations on the first symbol of the sequence, and fixations after an initial saccade to the target symbol were discarded from analysis. Trials were excluded from further analyses, if more than 15 symbols of the sequence were not fixated or if more than 7 symbols that did not belong to the sequence were fixated. Participants contributed between 14 and 49 trials with a mean of 36 trials. Overall, 62,420 fixations were retained for further analyses.

For all analyses, we calculated means of dependent variables for each participant separately and averaged the data subsequently. Whenever the dependent variable was a function of the landing site, the data were additionally divided into bins of equal size for each participant. By this procedure, each bin and each participant contributed equally to the analyses (independent of the number of fixations). Except for analyses of landing site distributions and refixation probabilities, empty bins were excluded from further analyses.

2.3 Results

An example of a participant's eye movements during the sequential search task is shown in Figure 2.2b. The eye's trajectory followed the path until the target symbol (a closed circle) was found. After preprocessing, the trajectories were divided into saccades and fixations (see Methods). Because scanpaths are complicated, there is no single measure of fixation duration which adequately captures the dynamics of eye movements (e.g., Rayner, 1998). The most frequent saccades are forward saccades from one symbol to the next on the path or saccades changing the fixation position within the same symbol (refixations). Examples of both saccade types are given in Figure 2.3a. All other types of saccades are less frequent by an order of magnitude. Regressions are saccades against the required movement direction, targeting a previously visited region of the display. In the example of Figure 2.3b a regression hits a previously fixated symbol on the path. Saccades that skip a symbol can be subdivided into two different categories, linear skippings (Fig. 2.3c) and oblique skippings (Fig. 2.3d). Skippings are frequently followed by a regression, which is illustrated in Figure 2.3d. In addition, participants produced saccades to symbols outside the required movement path (Fig. 2.3e), which we defined as saccadic errors.

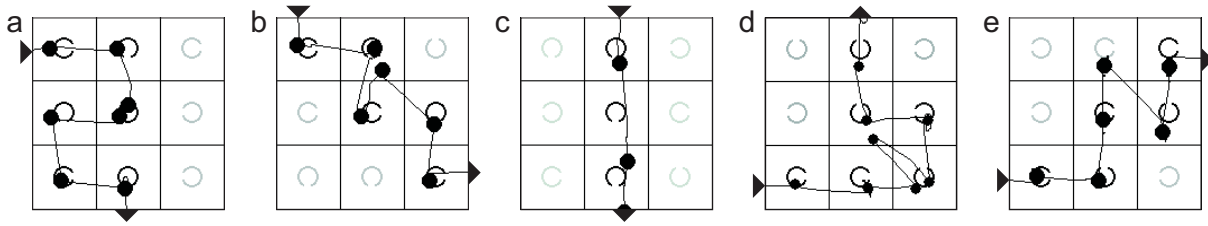


Figure 2.3: Classification of saccades and fixations. Straight horizontal and vertical lines around a symbol indicate the boundaries which we used to map fixation positions to symbols. For clarity, symbols on the path are highlighted in bold font. Arrow heads indicate the movement direction. (a) Forward saccades and a refixation. (b) A regression back to a previously fixated symbol. (c) Linear skipping of a symbol. (d) Oblique skipping of a symbol, followed by an immediate regression. (e) A saccade error to a symbol outside the required movement path.

2.3.1 Fixation probabilities and fixation durations

Overall performance can be summarized by fixation probabilities and by fixation durations. Here, we computed the probability for a fixation contingent on the subsequent saccade type and the corresponding mean fixation duration. The data in Table 2.1 are split by saccade type and gap size. In most cases (about 60%) participants produced forward saccades. Refixations on the same symbol were observed frequently (about a third of all saccades or 33%). Thus, these two saccade types represent 93% of all saccades. In contrast, other types of saccades occurred less frequently (regressions: 2.5%, linear skippings: 0.3%, oblique skippings: 0.2%, saccadic errors: 2.0%). As a consequence, we will focus on forward saccades and refixations for statistical analyses.

Table 2.1: Fixation probabilities and fixation durations by saccade type and gap size

| Gap Size | Forward Saccade | Refixation | Regression | Linear Skipping | Oblique Skipping | Error |
|------------------------|-----------------|------------|------------|-----------------|------------------|-------|
| Fixation Probability | | | | | | |
| Small | 0.576 | 0.366 | 0.025 | 0.002 | 0.001 | 0.020 |
| Medium | 0.625 | 0.321 | 0.024 | 0.002 | 0.002 | 0.017 |
| Large | 0.637 | 0.303 | 0.029 | 0.003 | 0.002 | 0.018 |
| Fixation Duration [ms] | | | | | | |
| Small | 303 | 243 | 305 | 324 | 376 | 313 |
| Medium | 296 | 231 | 285 | 277 | 258 | 297 |
| Large | 295 | 230 | 295 | 263 | 222 | 297 |

A repeated-measures analysis of variance (rmANOVA) was performed on fixation probability with saccade type (2 levels: forward saccade and refixation) and gap size (3 levels: small, medium, large) as factors. A main effect of saccade type was found, $F(1,22) = 68.14$, $p < 0.001$, as well as an interaction between saccade type and gap size, $F(2,44) = 75.75$, $p < 0.001$. No main effect of gap size was found, $F(2,44) = 1.87$, $p = 0.17$. Participants generated more forward saccades than refixations. The sum of forward saccades and refixations did not differ for different gap sizes. With increasing gap size,

however, the proportion of forward saccades increased while the proportion of refixations decreased.

The influence of gap size was visible in participants' fixation durations as well (Table 2.1). We performed a rmANOVA on fixation duration with saccade type (2 levels: forward saccades and refixations) and gap size (3 levels: small, medium, large) as factors. A main effect of saccade type, $F(1,22) = 74.23$, $p < 0.001$, confirmed that fixation durations before refixations were shorter than before forward saccades. A main effect of gap size was found, $F(2,44) = 11.39$, $p < 0.001$. Fixation durations increased with decreasing gap size. We observed no significant interaction between saccade type and gap size, $F(2,44) = 1.13$, $p = 0.33$.

In our sequential search task a serial scanning strategy was required, however, saccadic scanpaths turned out to be complex in both space (fixation probability) and time (fixation durations). First, saccades did not move as one-step jumps from one symbol to the next in the required sequence. Relative frequencies of saccade types were modulated by gap size of the fixated symbol. The proportion of refixations increased with decreasing gap size, while the proportion of forward saccades decreased with decreasing gap size. Second, average fixation duration varied with the upcoming saccade type and by gap size of the fixated symbol. As fixation duration depends on properties of stimuli during visual search (Gould & Dill, 1969; Hooge & Erkelens, 1998) and on properties of words during reading (Rayner, 1998; Kliegl et al., 2006), gap size induces an immediate effect on fixation duration. Finally, as previously reported by Hooge and Erkelens (1998) we observed saccadic errors. These saccades landed on symbols that were not part of the sequence. In summary, eye movements in our task are similar to saccades observed during previously studied search tasks and during reading, demonstrating that our task is adequate for the investigation of oculomotor effects.

2.3.2 Preferred viewing location

The variability in landing positions is related to various oculomotor phenomena. Here, we investigated distributions of within-symbol landing positions of all first fixations. Horizontal and vertical components of landing positions were analyzed separately (Fig. 2.4). One-sample t -tests determined whether mean fixation position over all first fixations deviated from the symbol's center. Generally, symbols were fixated in the center for both the horizontal component, $t(22) = -0.73$, $p = 0.47$, and the vertical component, $t(22) = 1.76$, $p = 0.09$, i.e., deviations from symbol centers were not significant. Two one-way rmANOVAs were conducted to test the influence of gap location (4 levels: top, bottom, left, right) on both mean horizontal and mean vertical landing sites. Even though mean landing sites on symbols with different gap position differed only marginally with a maximal difference of about 0.1° , we found an effect of gap location on mean horizontal landing site, $F(3,66) = 7.82$, $p < 0.001$, and mean vertical landing site, $F(3,66) = 11.93$, $p < 0.001$. Parameters (mean, standard deviation) of the estimated truncated Gaussian distributions are summarized in Table 2.2.

Next, a rmANOVA was performed to analyze the variability of landing positions with dimension (2 levels: horizontal and vertical components) and gap location (4 levels: top, bottom, left, right) as factors. Horizontal components were less variable than

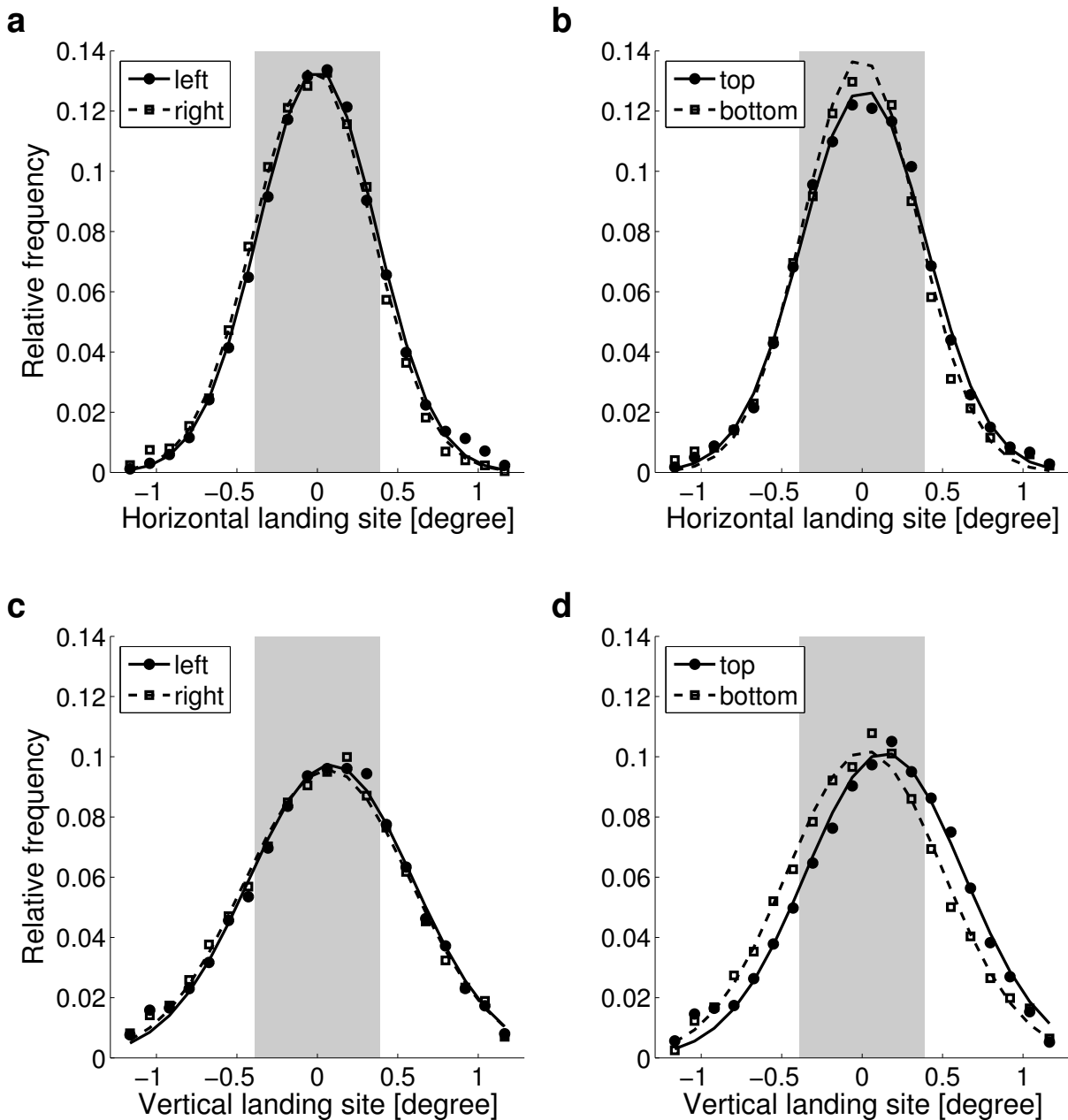


Figure 2.4: Preferred viewing locations within fixated symbols. Top panels: Distributions of the horizontal component of landing positions for symbols (a) with horizontal gap positions and (b) with vertical gap positions. Bottom panels: Corresponding distributions of the vertical component of landing positions for symbols (c) with horizontal gap positions and (d) with vertical gap positions. Experimentally observed distributions were fitted using truncated Gaussians. The gray areas indicate the extent of a single symbol, white areas represent spaces between symbols.

vertical components, $F(1,22) = 67.05$, $p < 0.001$. There was no main effect of gap location, $F(3,66) = 2.49$, $p = 0.07$, but an interaction of dimension and gap location, $F(3,66) = 12.81$, $p < 0.001$.

In accordance with previous observations, where fixations were located around the center of stimuli (Findlay, 1997; Henderson, 1993) or close to the word center during reading (e.g., Rayner, 1979), the mean landing position distribution of first fixations in our sequential search task was centered on the fixated symbol for both horizontal and

Table 2.2: Within-symbol fixation position: Preferred viewing location

| Gap Position | Horizontal Component [°] | | Vertical Component [°] | |
|--------------|--------------------------|------|------------------------|------|
| | Mean | S.D. | Mean | S.D. |
| Top | 0.01 | 0.39 | 0.14 | 0.49 |
| Bottom | -0.01 | 0.35 | 0.02 | 0.48 |
| Left | -0.00 | 0.36 | 0.08 | 0.51 |
| Right | -0.03 | 0.36 | 0.06 | 0.52 |

vertical components. Variability was somewhat larger for vertical compared to horizontal components.

2.3.3 Launch site effect and saccadic range error

A key finding in research on the preferred viewing location in reading is that landing sites are modulated by the distance of the launch sites of saccades (McConkie et al., 1988). To investigate such a modulation in our experiment, we examined this *launch site effect* (LSE) in detail. Because our task involves eye movements in two dimensions, we analyzed all 8 possible combinations of directions of saccade vectors (rightward, leftward, upward, downward) and components of the landing position (horizontal, vertical).

We expected greater modulations in the component of the landing site which is *parallel* to the saccade vector, i.e., the actual eye-movement direction. For example, when the saccade vector is oriented from left to right, the LSE should be greater in the horizontal than in the vertical component of the landing site distribution, since the component of the landing site perpendicular to the saccade vector is less relevant to the task. Ideally, the saccade vectors were strictly horizontally or vertically, which would simplify the saccade programming to a one-dimensional problem. Therefore, we hypothesized that the mean error in the component of the landing site, which is orthogonal to the saccade vector, would be roughly constant between two subsequent fixations.

Figures 2.5 and 2.6 summarize our experimental data on the LSE for horizontal and vertical saccade vectors, respectively. Distributions of landing site components were plotted for saccades from different launch sites. For the horizontal component, separate landing site distributions were calculated for launch sites to the left of the previously fixated symbol, launch sites at the center of the previous symbol, and launch sites to the right of the previously fixated symbol. For the vertical component, distributions were based on a subset of launch sites from above of the previously fixated symbol, from the center of the previous symbol, and from below of the previously fixated symbol. A glance at the figures indicates that landing site distributions are shifted towards the launch site. Landing site distributions of components parallel to the saccade vectors (Fig. 2.5a,b and and Fig. 2.6c,d) are broader compared to the corresponding distributions of the orthogonal components.

Next, we examined the exact relation between mean launch site and mean landing site, again separately for all 8 cases plotted in Figures 2.5 and 2.6. Generally, we define the launch site as the fixation position $\vec{v} = (v_x, v_y)$ within a symbol_{*n*} and the landing site as the fixation position $\vec{w} = (w_x, w_y)$ within the subsequently fixated symbol_{*m*}. Here, we restrict the analysis to all cases were (i) $m = n + 1$ and (ii) both symbols are members

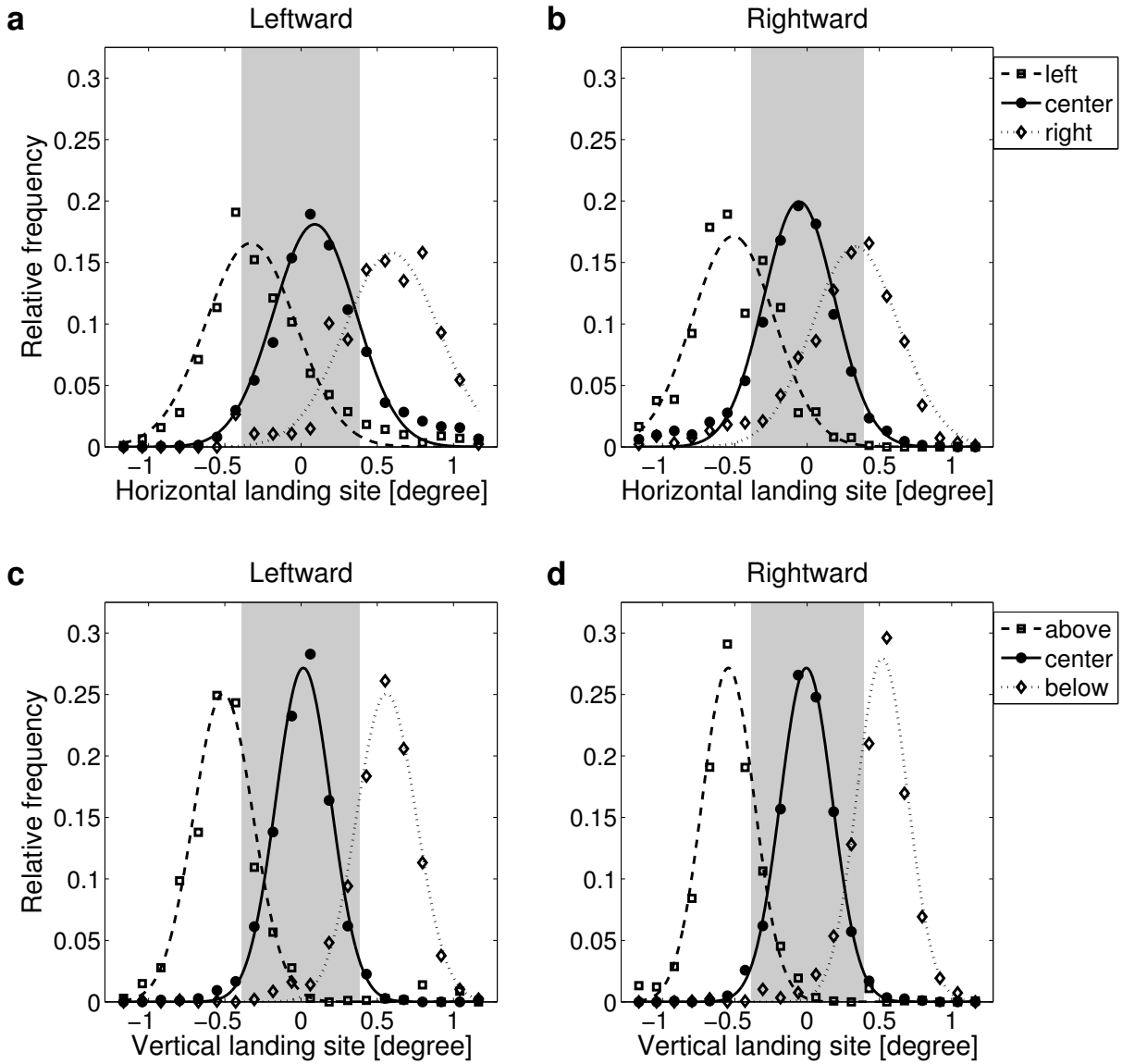


Figure 2.5: Launch site effect for saccades to the right and left. (a,b): Horizontal landing site distributions for launch sites to the left of, at the center, or to the right of a symbol. (c,d): Vertical landing sites after saccades launched above, below or the center of a symbol. Landing site distributions were calculated separately for the two possible saccade directions (left panels: saccades to the left; right panels: saccades to the right). Gray areas symbolize the position and extent of a symbol.

of the eye-movement path given by the task. From McConkie *et al.*'s (1988) work, we expected linear relations between the components of v_x, v_y and w_x, w_y , i.e.,

$$w_{xi} = \alpha_{xi} + \beta_{xi}v_{xi} \quad (2.1)$$

$$w_{yi} = \alpha_{yi} + \beta_{yi}v_{yi} \quad (2.2)$$

where i denotes the direction of the saccade vector³. The estimated parameters give insight into the relation between launch site and landing site, where α displays the mean

³Note, McConkie *et al.* (1988) used launch site distance rather than launch site. Due to the regular arrangement of the stimuli in this task, launch site distance can easily be converted to launch site. The slope β is unaffected by this transformation.

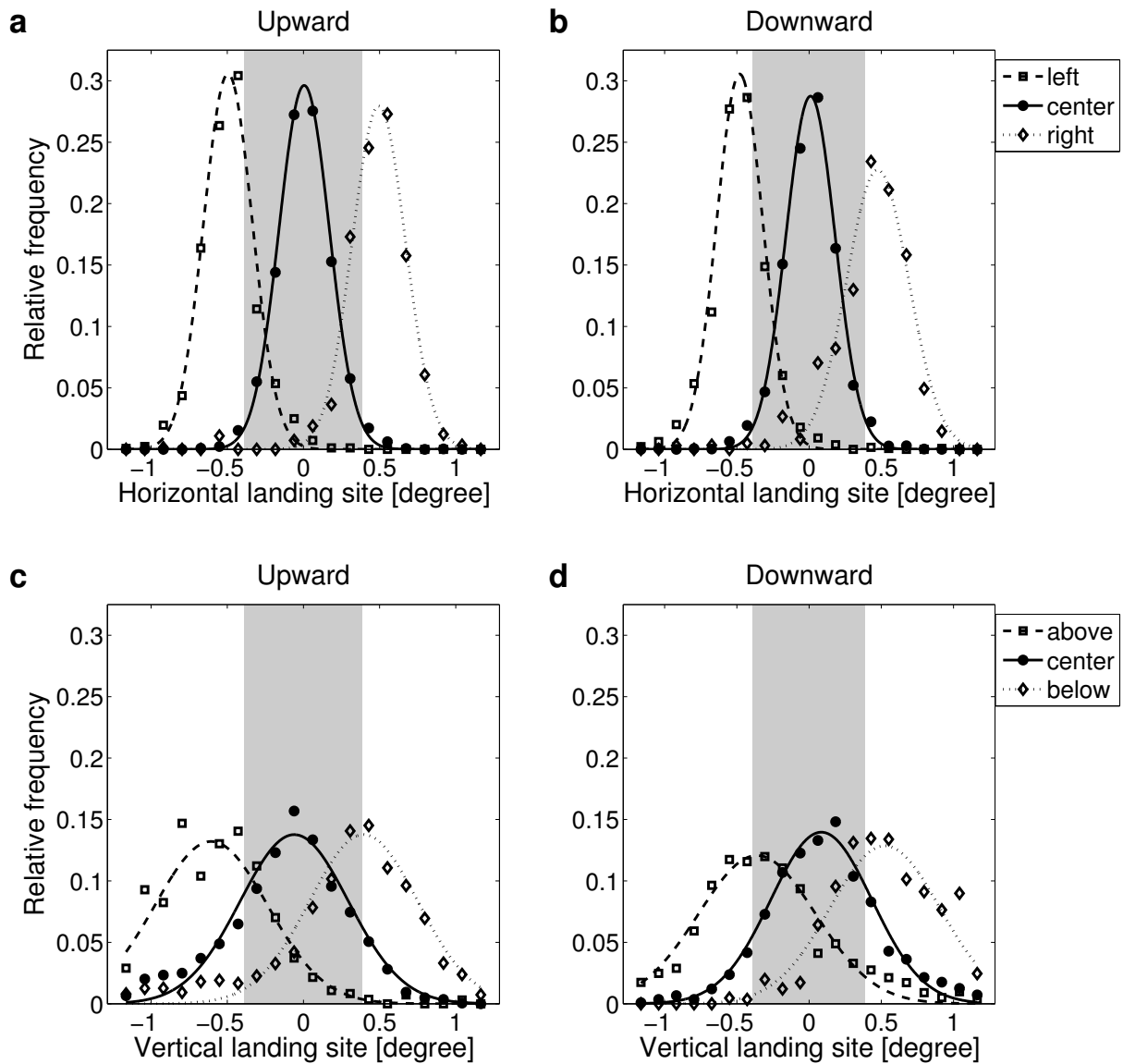


Figure 2.6: Launch site effect for upward and downward saccades. (a,b): Horizontal landing site distributions for launch sites to the left of, at the center, or to the right of a symbol. (c,d): Vertical landing sites after saccades launched above, below or the center of a symbol. Landing site distributions were calculated separately for the two possible saccade directions (left panels: upward saccades; right panels: downward saccades).

landing site for saccades launched from the center of a symbol and β gives the steepness of the linear function between launch site and landing site. A flat slope, i.e., $\beta = 0$, occurs when saccades from different launch sites are directed towards the same landing site. A slope of $\beta = 1$ is observed when saccades from different launch sites have the same average length. An influence of launch site on landing site (the LSE) will produce a slope between these two extremes. From our hypothesis we expected no LSE for the relation between perpendicular components, $\beta = 1$. In other words, the fixation error remains constant between two subsequent fixations. Moreover, the presence of a LSE for parallel components would be equivalent to $\beta > 0$ and $\beta < 1$.

In our data, we found linear functions between mean launch site and mean landing site, whenever the saccade was launched from within a symbol (Fig. 2.7), between about

2. Oculomotor control

-0.6° and $+0.6^\circ$. The linear relation breaks down for larger deviations of the launch site from a symbol's center. Therefore, we estimated linear fits only for mean launch sites within a symbol's borders. With increasing distance of the launch site from a symbol, the subsequent landing site increasingly deviated from the predicted landing site. This deviation, however, always shifted the mean landing site towards the center of the next symbol. For launch sites from the symbol, estimated parameters (intercepts α and slopes β) are given in Table 2.3. The results indicate that the LSE was greater for landing site components parallel to the saccade vector; numerically, we observed $\beta \approx 0.70$ for parallel components and $\beta \approx 0.85$ for perpendicular components.

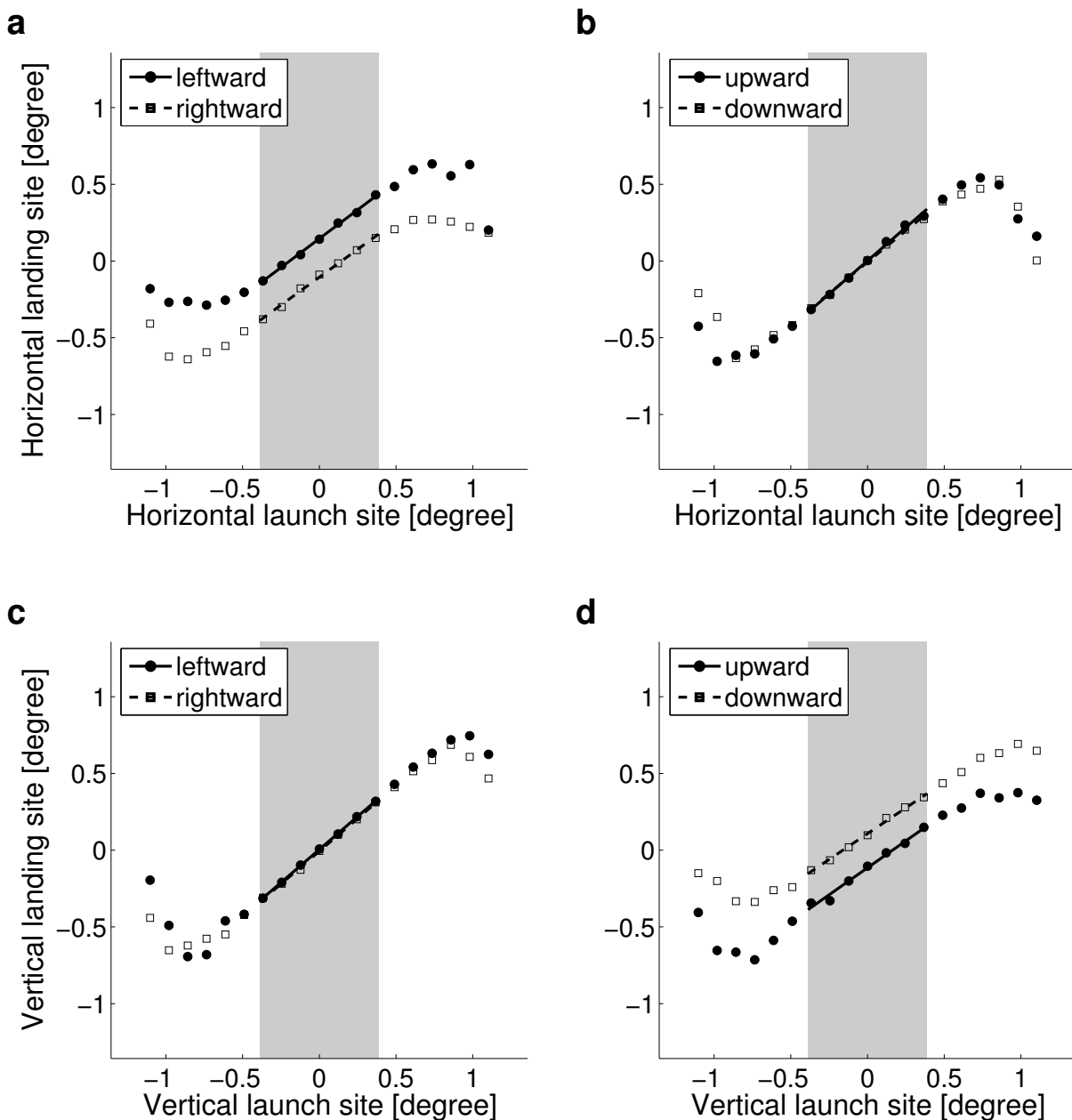


Figure 2.7: Numerical calculation of the saccadic range error. Mean landing sites as a function of launch site split by (a,b) horizontal launch site component and (c,d) vertical launch site component. Saccadic range errors were calculated separately for horizontal (left panels) and vertical saccade vectors (right panels).

Table 2.3: Saccadic range error

| Saccade direction i | Landing site component | | | |
|-----------------------|-----------------------------|--------------------|---------------------------|--------------------|
| | Horizontal component, w_x | | Vertical component, w_y | |
| | Slope β | Intercept α | Slope β | Intercept α |
| upward | 0.87 | 0.00 | 0.70 | -0.11 |
| downward | 0.82 | -0.01 | 0.67 | 0.11 |
| leftward | 0.75 | 0.15 | 0.86 | 0.00 |
| rightward | 0.73 | -0.11 | 0.86 | -0.01 |

Separate rmANOVAs were performed on horizontal and vertical landing site components with mean launch site (7 levels: all launch sites within a symbol) and main movement direction (4 levels: upwards, downwards, leftwards, rightwards) as factors. In general, landing positions were shifted towards the launch site. This result was found both for mean horizontal, $F(6, 132) = 1274.73$, $p < 0.001$, and mean vertical landing sites, $F(6, 132) = 894.49$, $p < 0.001$. Furthermore, we observed an effect of the saccade vector direction on mean horizontal, $F(3, 66) = 26.68$, $p < 0.001$, and mean vertical landing sites, $F(3, 66) = 15.57$, $p < 0.001$. Landing site components parallel to the saccade vector were shifted towards the previous symbol from which the saccade was launched. Therefore, saccades had a tendency to slightly undershoot the center of a symbol after a forward saccade. In contrast, in the component perpendicular to the saccade vector, saccades tended to land at a symbol's center. Interactions of launch site and saccade direction were observed both for mean horizontal, $F(18, 396) = 5.49$, $p < 0.001$, and mean vertical landing sites, $F(18, 396) = 6.27$, $p < 0.001$, and are reflected by slope differences for different saccade directions. The linear function between mean launch site and mean landing site was shallower when the landing site corresponded to the saccade direction. A horizontal saccade vector, either to the left or to the right, caused shallower slopes for horizontal landing sites components, while a vertical saccade vector produced shallower slopes for vertical landing sites.

The *saccadic range error* during reading produces a slope of about 0.5 (McConkie et al., 1988). In our experiment all slopes were smaller than 1 but differed between landing site components parallel or perpendicular to the saccade movement direction. For the landing site component parallel to the saccade vector, slopes were about 0.7, while slopes for components perpendicular to the saccade vector were about 0.85. Thus, mean landing site components parallel to the saccade vector were corrected towards the symbol's center, while landing site components perpendicular to the saccade vector had a stronger tendency to maintain the deviation from the symbol's center observed at the launch site.

Our results extend the findings of (Vergilino-Perez & Findlay, 2006), who reported that the relation between launch site and landing site differs for within-object (slopes ~ 1.0) and between-object saccades (slopes: ~ 0.5). In our analysis, all saccades were between-object saccades and slopes were between 0.5 and 1. As a new finding, however, we demonstrated that the size (or slope) of the saccadic range error depends on the question whether we analyze error parallel or perpendicular to the saccade vector.

As during reading, preceding launch sites influenced landing site distributions of initial fixations in our sequential search task. The saccadic range error (McConkie et al.,

1988) was observed for both horizontal and vertical eye movements, but differed for the components parallel or perpendicular to the saccade vector.

2.3.4 Refixation probability and optimal viewing position

Operationally, the optimal viewing position (OVP) can be defined as the position with a minimum refixation probability (e.g., Vitu et al., 1990, for the case of reading and isolated word recognition). In our sequential search task, we can expect an OVP at the symbol's center. Following our analysis of the preferred viewing location, we performed calculations of refixation probabilities separately for the two factors gap orientation (left/right vs. top/bottom) and component of the landing position (horizontal vs. vertical).

A glance at the resulting plots (Fig. 2.8) indicates the surprising finding that gap orientation strongly interacts with component of the landing position. For gap orientations perpendicular to the component of the landing position, a quadratic curve is observed, which indicates an optimal viewing position at the symbol's center (Fig. 2.8b,c). Interestingly, when gap orientations are parallel to the component of the landing position studied, a linear relation between refixation probability and landing position is observed, where the probability decreases towards the gap position (Fig. 2.8a,d). Thus, an OVP does not exist in the latter case.

Two factors might have contributed to the absence of the OVP effect in the landing position component parallel to the gap orientation. First, the likelihood of undershooting the next symbol increases with increasing distance to the next symbol. In this case, refixations will be more likely when the first fixation is on the side opposite to the next symbol. Second, for saccadic movements parallel to the landing site component, refixations might not be needed to correct deviations from the center of a symbol. Slopes of the SRE revealed that fixational deviations are corrected less when landing site components are perpendicular to the movement direction (slopes: ~ 0.85) compared to landing site components parallel to the movement direction (slopes: ~ 0.7). As a consequence for perpendicular landing site components, deviations to both sides of a symbol's center have to be corrected by refixations, causing quadratic OVP curves. In contrast, errors on the landing site component parallel to the movement direction are compensated by the upcoming saccade, resulting in the absence of quadratic OVP curves.

Next, we investigated whether the OVP effect for landing position components perpendicular to gap orientations was statistically reliable. We calculated quadratic fits (Nuthmann et al., 2005) to estimate the relation between landing position x and refixation probability $p(x)$ using three parameters,

$$p(x) = A_0 + B_0(x - C_0)^2, \quad (2.3)$$

where A_0 is the intercept, C_0 is the position of the minimum, and B_0 is a measure of the strength of the OVP effect.

OVP curves could not be estimated on the level of participants, because mean refixation rate in different bins was too noisy. Therefore, we employed a bootstrap method to create a sample of more stable refixation probabilities. Efron and Tibshirani (1993) proposed an algorithm to estimate standard errors in this type of data reliably. One thousand

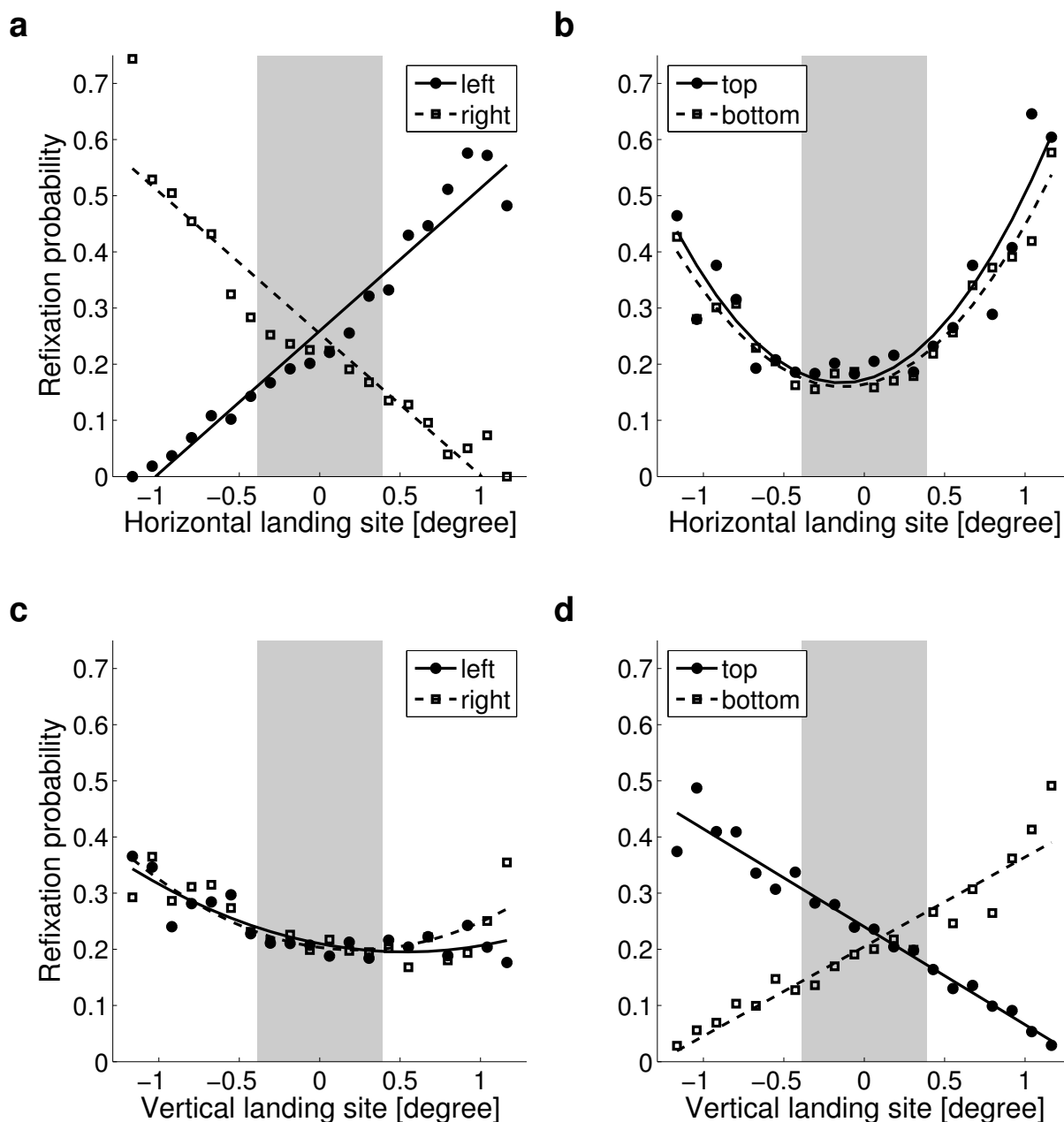


Figure 2.8: Refixation probabilities as a function of landing position. (a,d) For gap orientations parallel to the component of the landing position considered, a linear decrease towards the gap position within the symbol is found. (b,c) For gap orientations perpendicular to the component of the landing position, a quadratic curve is observed, which indicates an optimal viewing position at the symbol's center. The gray area displays the extent of a single symbol, white areas represent the space between two symbols.

bootstrap samples were selected, each consisting of 23 individual refixation rate patterns. Samples were drawn with replacement from the pool of observed individual refixation probabilities, i.e., in a given bootstrap sample, participants could be included 0 to N times. Over the whole set of replications, participants' data were included almost equally often. For each replication, parameters of the OVP curves were based on the bootstrap's mean refixation probabilities. Standard deviations of the various parameters across 1000 replications approximate the standard errors of means (Efron & Tibshirani, 1993), which, in turn, were used to compute confidence intervals. Thus, the mean across

the bootstrap samples corresponds to the mean over all subjects, while the standard deviations reflect the stability of mean. Table 2.4 provides the mean parameters over all bootstrap samples and 95% confidence intervals. Significant parameters were found, whenever the confidence interval around a mean value did not overlap with 0. The same bootstrap sample was used to calculate parameters for horizontal and vertical components of landing sites as well as for different symbols and were consequently treated as paired samples in subsequent analyses.

Averaged estimated parameters of 1000 bootstrap samples and 95% confidence intervals are reported in Table 2.4. The bootstrap data support the existence of a horizontal OVP. Confidence intervals of 95% demonstrate that the horizontal OVP is slightly left of the symbol's horizontal center when symbols point upwards (-0.149 ± 0.101) or downwards (-0.135 ± 0.092). Parameter B_0 reveals significant costs for not fixating at the OVP (top: 0.258 ± 0.100 , bottom: 0.225 ± 0.086). Minimum refixation probability is given by parameter A_0 . Estimated parameters of vertical landing sites were less stable. Even though, the mean estimates of the bootstrap were similar to the observed parameters, no reliable OVP could be computed. Confidence intervals of the OVP, parameter C_0 , exceeded the symbol's borders (left: 0.675 ± 5.047 , right: 0.239 ± 1.136). Costs associated with the distance to the OVP (parameter B_0) did only marginally differ from 0 (left: 0.050 ± 0.043 , right: 0.082 ± 0.060).⁴

Table 2.4: Statistical evaluation of the optimal viewing position

| Landing Position | Gap | Data | A_0 | B_0 | C_0 |
|------------------|--------|------|-------------|-------------|-------------|
| Horizontal | Top | Mean | 0.167 | 0.258 | -0.149 |
| | | CI | ± 0.034 | ± 0.100 | ± 0.101 |
| | Bottom | Mean | 0.159 | 0.225 | -0.135 |
| | | CI | ± 0.030 | ± 0.086 | ± 0.092 |
| Vertical | Left | Mean | 0.192 | 0.050 | 0.675 |
| | | CI | ± 0.107 | ± 0.043 | ± 5.047 |
| | Right | Mean | 0.199 | 0.082 | 0.239 |
| | | CI | ± 0.032 | ± 0.060 | ± 1.136 |

In summary, the qualitative form of the refixation probability depended on gap orientation and on landing position component. First, refixation probability linearly decreased towards the next symbol in the sequence, when the gap orientation was parallel to movement direction. Second, an OVP with a quadratic trend of the refixation probability was observed (Vitu et al., 1990; Nuthmann et al., 2005, 2007), when the movement direction was perpendicular to the component of the landing position considered. The OVP effect was not statistically reliable for the vertical component of the landing position.

⁴Additionally, we compared parameters of horizontal landing sites between both symbols. Since all probabilities were based on paired samples, we calculated the difference of each parameter for every bootstrap sample and subsequently estimated 95% confidence intervals to identify deviations from 0. Parameters did not differ between both horizontal estimates ($\Delta A_0 = 0.007 \pm 0.036$, $\Delta B_0 = 0.033 \pm 0.103$, $\Delta C_0 = -0.014 \pm 0.131$). We did not compare vertical landing sites, since vertical OVP curves could not be reliably estimated.

2.3.5 Inverted optimal viewing position

The existence of an optimal viewing position in reading suggested that the minimum of the processing time and, hence, fixation duration should be observed close to the word center. However, mean fixation durations tend to be longer near the word center compared to word edges. As a consequence, this counterintuitive phenomenon was termed the inverted optimal viewing position effect (IOVP; Vitu et al., 2001; Nuthmann et al., 2005, 2007).

Fixation durations at different landing positions on various symbols are shown in Figure 2.9. Fixation durations are modulated by both landing position and gap orientation of the fixated symbol. First, the IOVP effect is present in all eight combinations of both factors. Second, the effect is larger for horizontal landing positions, but even the flatter relations for vertical landing sites have a magnitude similar to the IOVP effect during reading.

For the statistical evaluation, we fitted IOVP curves, i.e., fixation duration $f(x)$ as a function of position x , using quadratic polynomials (Nuthmann et al., 2005, 2007),

$$f(x) = A_1 + B_1(x - C_1)^2. \quad (2.4)$$

Separate analyses were performed for horizontal vs. vertical landing positions and for different gap orientations. In Equation (2.4), parameter C_1 represents the fixation position with maximum fixation duration, while parameter A_1 indicates the maximum fixation duration. Parameter B_1 is the slope of the parabolic curve and quantifies the decrease in fixation duration for not fixating at the IOVP. Averaged parameters and 95% confidence intervals of 1000 bootstrap samples are given in Table 2.5. Bootstrap samples were computed as described in the previous section.

Table 2.5: Statistical evaluation of the inverted optimal viewing position effect

| Gap | Data | Horizontal landing position | | | Vertical landing position | | |
|--------|------|-----------------------------|----------|-------------|---------------------------|----------|--------------|
| | | A_1 | B_1 | C_1 | A_1 | B_1 | C_1 |
| Left | Mean | 318 | -83 | -0.338 | 308 | -48 | 0.231 |
| | CI | ± 16 | ± 22 | ± 0.139 | ± 16 | ± 16 | ± 0.150 |
| Right | Mean | 314 | -77 | 0.244 | 309 | -55 | 0.242 |
| | CI | ± 16 | ± 32 | ± 0.187 | ± 16 | ± 18 | ± 0.147 |
| Top | Mean | 305 | -128 | 0.007 | 329 | -13 | 2.245 |
| | CI | ± 16 | ± 18 | ± 0.041 | ± 514 | ± 17 | ± 26.879 |
| Bottom | Mean | 346 | -131 | -0.066 | 342 | -48 | -0.232 |
| | CI | ± 16 | ± 31 | ± 0.061 | ± 20 | ± 19 | ± 0.193 |

For horizontal landing sites, IOVP curves were shifted towards the location of the gap within the symbol. Since parameters for different curves were based on the same bootstrap sample, we computed the difference between two parameters for each sample and tested subsequently, whether the mean difference deviated from 0.⁵ Surprisingly, the

⁵The IOVP of symbols with a gap to the left was left of symbols with a gap at the center (top: -0.345 ± 0.145 ; bottom: -0.272 ± 0.153), while the IOVP of symbols with a gap to the right was shifted to the right (top: 0.237 ± 0.179 ; bottom: 0.310 ± 0.173). IOVPs of symbols with a gap at the top or bottom did not differ (0.073 ± 0.074).

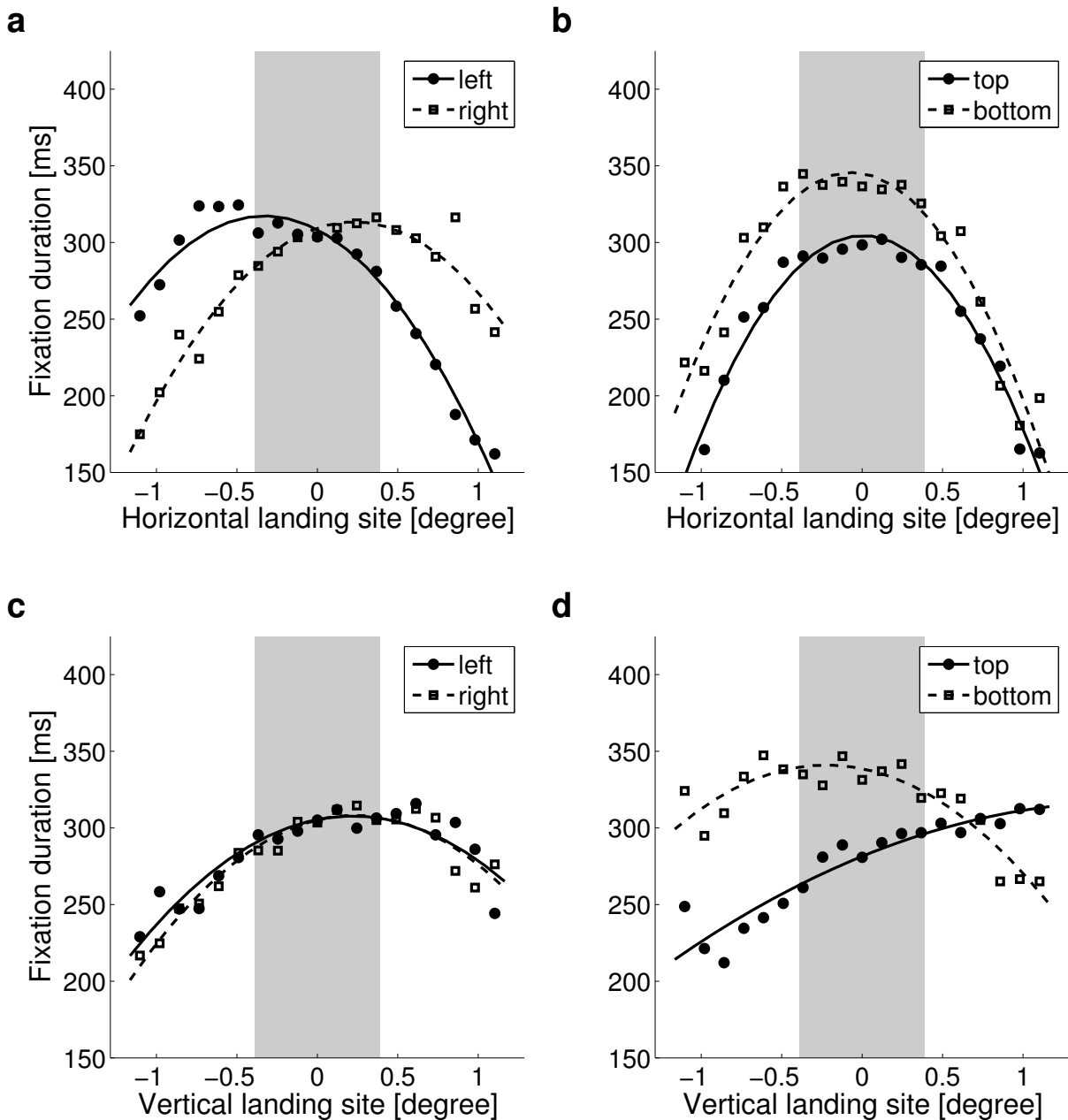


Figure 2.9: The inverted optimal viewing position effect for all first fixations. (a,b) Mean fixation durations at different horizontal landing positions show a pronounced inverted U-shape. Lines represent estimated quadratic curves of fixations on symbols with horizontal vs. vertical gap orientation. (c,d) Mean fixation durations at different vertical landing positions. The gray area displays the extent of a single symbol, white areas represent the space between two symbols.

observed IOVP corresponded approximately to the horizontal gap location (left: -0.35° ; top, bottom: 0.0° ; right: 0.35°). Values of the parameter B_1 indicated clear quadratic relations between horizontal landing site and fixation duration. Fixation durations decreased with increasing horizontal distance to the IOVP for all symbols. In addition, maximum fixation duration, determined by parameter A_1 , significantly differed between various symbols.

In the case of the vertical component of the landing position, IOVP curves were shifted towards the gap. Fits of IOVP curves, however, could not reliably be estimated,

when the gap pointed upwards. Confidence intervals of the position with maximum fixation duration exceeded even the symbol's boundaries. These IOVP parameters were omitted from further analyses. Vertical IOVP curves of symbols with a gap pointing downwards, to the right, or to the left were less variable. When the gap was at the bottom of a symbol, the mean IOVP was shifted towards the gap location (-0.232 ± 0.193) and significantly deviated from symbols with a gap to the left (left: 0.463 ± 0.215) and right (right: 0.474 ± 0.211). Vertical IOVPs on symbols with a gap at the vertical center were located slightly above of the symbol's center (left: 0.231 ± 0.150 ; right: 0.234 ± 0.147) and did not differ from each other (0.011 ± 0.129). Parameter B_1 displayed quadratic trends for the three stable IOVP curves and maximum fixation durations (parameter A_1) could reliably be estimated.

Landing position had a strong impact on average fixation duration by producing an inverted U-shaped behavior. Except for vertical landing sites on symbols with a gap at the top, IOVP curves could reliably be estimated and the position with maximum fixation duration was generally shifted towards the gap location. In all estimated vertical IOVP curves, there was a general upward shift of the location with the maximum fixation duration.

2.4 Discussion

2.4.1 Summary

In the present study, we observed several effects of fixation position on eye-movement behavior, which are related to principles of oculomotor control. In our sequential search task, we varied gap size as a measure of processing difficulty. First, gap size of the fixated symbol produced an immediate effect on fixation duration and probability of target selection for the next saccade. The eyes fixated more difficult symbols longer and refixated them more often.

Second, we found effects of the relative fixation position within a symbol on subsequent fixations. While the eyes seemed to fixate at a preferred viewing location (PVL), i.e., near the horizontal and vertical center of a symbol, this data set confirmed that the landing position distribution around the PVL is a compound distribution of landing site distributions from different launch sites. The launch site effect (LSE) causes landing positions to be shifted towards the preceding fixation position irrespective of the saccade direction. A linear relation between launch site and landing site occurred when the saccade was launched from a symbol, but disappeared with increasing distance of the fixation position to the center of a symbol.

Third, effects were not limited to subsequent landing sites, since we found modulations of fixation durations and refixation probabilities. Fixations lasted longer near the gap position. With increasing distance to the gap location fixation durations decreased, producing an inverted U-shaped relation (IOVP effect). The effect was more pronounced for horizontal eye movements but was visible for vertical landing sites as well. In addition, landing sites influenced refixation probabilities. An optimal viewing position (OVP), which is indicated by a pronounced minimum of the refixation probability, was only found

for the landing position component perpendicular to the saccade vector. Interestingly, we observed that refixation rates linearly decreased towards the next symbol in the landing position component parallel to the saccade vector. Even though an optimal viewing position (OVP) does not exist in these cases, deviations from the center of a symbol were corrected by successive saccades. Slopes values of the saccadic range error (SRE) reflect the strength of control of deviations, i.e., a slope value close to one indicates no error correction, while a slope value close to zero leads to a landing site at PVL.

More specifically, we observed steeper slopes for landing site components perpendicular to the movement direction than for landing site components parallel to the movement direction. For landing site components perpendicular to the movement direction, saccadic errors to both sides of the symbol were not entirely adjusted by saccades to the next symbol. Instead, refixations had to correct the deviations, causing quadratic OVP curves. In contrast, deviations on the landing site component parallel to the movement direction were compensated by saccades to the next symbol, leading to a linear decrease of the refixation rate towards the next symbol.

These findings provide important insights into the relation between the preferred viewing location (PVL), optimal viewing position (OVP), and inverted optimal viewing position (IOVP). A systematic relation might naturally be assumed, since, in the case of reading, all effects produce a local maximum (PVL, IOVP) or minimum (OVP) near the word center (PVL: Rayner, 1979; IOVP: Vitu et al., 2001; Nuthmann et al., 2005; OVP: McConkie et al., 1989; Vitu et al., 1990; Nuthmann et al., 2005). Our results show that all three effects are not strictly coupled, because the effects are not centered around the same location in our experiment. Generally, this finding suggests that the effects might be related to different principles of oculomotor control. More specifically, we observed that

- the PVL was generally located near the center of each symbol, however, there were small but reliable effects showing that the horizontal component of the PVL was shifted away from the gap, while the vertical PVL was shifted towards the gap location,
- the maximum of the IOVP effect was always shifted towards the most informative location, which is the gap location in our task, and
- the OVP, which is indicated by a minimum of the refixation probability, did only exist with respect to the landing position component perpendicular to the saccade vector.

2.4.2 Implications for eye-movement control

Most research on the influence of relative fixation position on eye movements was confined to reading (Rayner, 1979; McConkie et al., 1988, 1989; Vitu et al., 1990, 2001; Nuthmann et al., 2005; Hyönä, 1995; White & Liversedge, 2006) or mindless reading (Vitu et al., 1995; Rayner & Fischer, 1996; Nuthmann et al., 2007). As a consequence, analyses in these effectively one-dimensional tasks were limited to horizontal saccades and fixation positions. As an exception, Henderson (1993) investigated horizontal and vertical eye movements during processing of line-drawings and reported a PVL, IOVP, and OVP. In

order to fixate each object in an array, both horizontal and vertical saccades were required. However, horizontal and vertical eye movements were averaged, which precluded the analysis of finding specific effects in both dimensions. In our study, we observed both a PVL and an IOVP for horizontal and vertical fixation positions. An OVP was found in both dimensions but was restricted to eye movements perpendicular to the saccade vector. The magnitudes of the effects differed substantially between horizontal and vertical eye movements. Differences might be expected since horizontal and vertical components of the saccade vector originate in different nuclei of the brainstem (e.g., Sparks, 2002). These differences in neural control have important consequences, for example, peak velocities are smaller for vertical than for horizontal saccades. Our results clearly suggest that the analysis of saccadic behavior must be performed separately for both dimensions and, moreover, contingent on the orientation of the saccade vector.

When comparing the influence of relative fixation position on eye-movements across tasks, the observed similarities are remarkable. PVLs and IOVPs were present during reading, mindless reading, and sequential search. An important difference, however, was observed in the magnitude of the IOVP effect across tasks. The IOVP effect was larger during sequential search or mindless reading than during reading. Referring to work on the physiology of saccade programming, Findlay et al. (2001; see Dorris, Paré, & Munoz, 1997; Everling, Paré, Dorris, & Munoz, 1998) suggested that the activity in the rostral colliculus region causes differences in the fixation duration at various locations. According to their hypothesis, the activity of the rostral colliculus region is influenced by visual stimulation. As a consequence, fixations on objects increase the activity relative to fixations on blank sites. This explanation is in agreement with a stronger IOVP in the sequential search task. Blank sites were much larger than the gap between two words in reading. However, pure visual stimulation would not shift the IOVP onto the gap location. Furthermore, differences between reading and mindless reading would not be expected since the size of the blank space between words was the same. A comparison of the IOVP effect across tasks indicates that the magnitude of the IOVP is not solely related to visual stimulation. Some higher level processing causes shifts of the IOVP curves as well as differences in magnitude. Interestingly, IOVP effects increase with increasing fixation duration. This is a prediction from a model of the IOVP effect proposed by Nuthmann et al. (2005; see also Engbert et al., 2007; Nuthmann et al., 2007).

Although we did not observe an obvious relation between PVL, IOVP, and OVP, our results reveal where these effects will be expected in other tasks. The PVL was located near the center of a symbol for all gap locations, i.e., the position closest to all four possible gap locations. When the gap location is unknown, a saccade to the center of a symbol will on average land closest to the position with task relevant information. Even though saccades were directed towards the center of a symbol, IOVP curves were shifted towards the gap location. Fixation durations were longest at the gap location. It seems to us that saccades aim at the location within an object closest to all positions likely to contain task relevant information. Due to saccadic errors landing sites will be distributed across the symbol and fixation durations can subsequently be adapted according to the information at the actual fixation position.

Although PVL and IOVP are quite similar across tasks, large differences are obvious in the observed refixation patterns. During sequential search, OVPs were only present

when the component of the fixation position was perpendicular to the saccade vector. Obviously, refixation characteristics result from a combination of the PVL, IOVP, and saccadic errors. Depending on their dynamics, linear or even quadratic curves can be observed and the resulting form of the refixation rates reflects current task demands. Predictions of this complex behavior, however, might only be derived from computational models of eye-movement control.

2.4.3 Implications for theoretical models

The existence of a pronounced IOVP effect in our sequential search paradigm might help to improve current theoretical models of eye-movement control. Fixation durations are longest at the spatial position within a symbol, which is most informative to the task, both in horizontal and vertical dimensions. Most advanced theoretical models were developed for eye-movement control during reading (for an overview see Reichle et al., 2003). Nevertheless, we suspect that our results will have important implications for these models. For example, our own model of saccade generation during reading (SWIFT; Engbert et al., 2005) was expected to be generalizable to a range of tasks other than reading. Here, we focus on different theoretical models, which were proposed to explain the IOVP effect.

First, McDonald et al. (2005) proposed a model of eye movement control in reading with a built-in mechanism generating the IOVP effect. Because of the physiologically motivated vertical split of the fovea, two different control units are assumed to inhibit time-keeping of the current fixation duration. According to McDonald et al.'s model, such an inhibition produces longest fixation durations, whenever a word is fixated close to the center. Obviously, the IOVP effect in the vertical dimension cannot be explained because of a lacking horizontally split fovea.

Second, the most recent version of the E-Z Reader model (Pollatsek, Reichle, & Rayner, 2006) is able to reproduce the IOVP effect for the first of multiple fixations. Such an explanation, however, cannot account for the IOVP effect in single fixations, which is the most challenging effect for cognitive models of saccade generation. Furthermore, the explanation of the IOVP effect favored by Pollatsek et al. (2006) is tightly related to word processing, which is absent in our sequential search task.

Third, the IOVP effect in reading might be based on the correction of oculomotor errors (Nuthmann et al., 2005, 2007; Engbert et al., 2007). Broad distribution of within-word landing positions indicate that some saccades might be misguided and hit on a neighboring word. Nuthmann et al. assumed that fixation duration in the case of such a mislocated fixation is reduced because of the immediate triggering of an error-correcting saccade program. Because overlapping landing position distributions produce a higher proportion of mislocated fixations near the word boundaries, fixation durations are decreased towards word edges due to the error-correcting saccades. In our task, however, landing position distributions do not overlap. Therefore, for an analogous explanation of the IOVP in our task, we must assume that fixations on spaces between symbols count as mislocated fixations as well. An even more complicated problem for the explanation of the IOVP effect by mislocated fixations is that we observed a shift of the IOVP towards the gap location. Such a shift, however, is highly compatible with the perceptual economy

hypothesis (Vitu et al., 2001, p. 3531) suggesting “that the perceptuo-oculomotor system learns to produce longer fixations at locations where greater information is anticipated, based on prior experience”. In this current form, however, this hypothesis is more a description data pattern than a theoretical principle.

Research on eye movements during reading has greatly benefitted from the development of computational models (e.g., Engbert et al., 2005; McDonald et al., 2005; Pollatsek et al., 2006; Reilly & Radach, 2006). Effects of within-symbol fixation position studied here may be looked upon as additional benchmarks for current computational models. Large similarities were observed between oculomotor control during our sequential search task, reading, mindless reading, and other visual search tasks. As a consequence, we conclude that oculomotor control is based on a number of generic principles, which facilitate theory building in the field of eye-movement control (Liversedge & Findlay, 2000).

2.4.4 Conclusions

The important implication of our results is that the within-symbol fixation position strongly affects subsequent eye movement behavior. Effects are observed on current fixation duration, probability to refixate the symbol, and landing position of the next saccade. The launch site effect (LSE) and the inverted optimal viewing position (IOVP) were found both for horizontal and vertical components of fixation positions and turned out to be robust across tasks, while refixation rates vary across dimensions and substantially reflect task demands. Contrary to expectations, PVL, IOVP, and OVP are not trivially related to each other. Even short fixation durations do not obligatorily cause an increased refixation rate. In general, the eyes are directed towards the position closest to locations likely to contain task relevant information. Fixation durations are subsequently adjusted according to information available at the exact fixation position.

2.5 Acknowledgments

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Chapter 3

Eye movements in a sequential scanning task: Evidence for distributed processing

Hans A. Trukenbrod and Ralf Engbert
University of Potsdam, Germany

Running Head: Distributed processing

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Abstract

Current models of eye movement control are derived from theories assuming serial processing of single items or from theories based on parallel processing of multiple items at a time. This issue has persisted because most investigated paradigms generated data compatible with both serial and parallel models. Here we study eye movements in a sequential scanning task, where stimulus n indicates the position of the next stimulus $n + 1$. We investigate whether eye movements are controlled by sequential attention shifts when the task requires serial order of processing. Our measures of distributed processing in the form of parafoveal-on-foveal effects, long-range modulations of target selection, and skipping saccades provide evidence against models strictly based on serial attention shifts. We conclude that our results lend support to parallel processing as a strategy for eye-movement control.

3.1 Introduction

Whether items are processed serially or in parallel has led to enduring controversies in psychology (Logan, 2002). While this distinction might be subtle in some cases, the consequences for theories of movement planning are fundamental. For example, development of theories on eye-movement control is strongly influenced by the two diverging model categories of serial attention shifts and parallel processing of words (Reichle, Liversedge, Pollatsek, & Rayner, 2009). Even though an empirical distinction of these model classes is difficult, differences are theoretically important because of the models' predictions on limitations of cognitive capacities (Townsend, 1990). Here we analyzed eye-movement control in a sequential task where each stimulus informs about the location of the next stimulus, a paradigm developed to maximize the chances to observe serial control. We focus on effects of distributed processing by analyzing (i) modulations of fixation durations and target selection by upcoming stimulus elements and (ii) skipping saccades to formulate tests of sequential attention shifts as the basis of eye movement control.

Eye movements probably represent the most sensitive behavioral measure to investigate ongoing cognitive processing (Rayner, 2009). Because of acuity limitations of the visual system, our eyes continuously scan the environment to foveate areas of interest. As a consequence, visual perception is an active process critically based on eye movements (Findlay & Gilchrist, 2003). Since attention and eye movements are closely coupled, eye-movement measures can be used to infer attentional processes (Deubel & Schneider, 1996; Kowler et al., 1995). A crucial observation is that attention can be divided to multiple unconnected spatial locations at least in some of the tasks requiring sequences of saccades (Baldauf & Deubel, 2008; Gersch, Kowler, Schnitzer, & Doshier, 2009; Godijn & Theeuwes, 2003). Furthermore, Bichot, Rossi, and Desimone (2005) showed that features of stimuli are processed in parallel while eye movements add a serial component by moving selected stimuli for closer inspection onto the fovea, that is, the part of the retina with highest visual acuity.

In recent years, considerable progress has been made to understand eye movements in complex tasks that require long sequences of fixations. Integration of perceptual, cognitive, and oculomotor levels has led to a number of models on eye-movement control during reading (e.g., Engbert et al., 2005; Reichle et al., 1998), visual search (e.g., Najemnik & Geisler, 2005), and scene perception (e.g., Itti & Koch, 2001; Nuthmann, Smith, Engbert, & Henderson, 2010). However, this progress on computational models has not resolved the debate on serial versus parallel modeling frameworks (Engbert & Kliegl, 2011).

3.1.1 SAS models and E-Z Reader

Originally developed as a model for eye movements in reading, the E-Z Reader model (Reichle et al., 1998; Reichle, Warren, & McConnell, 2009) has developed into an important heuristic tool for the interpretation of eye-movement tasks (Reichle et al., 2012). The model represents the class of sequential attention shift (SAS) models and postulates that allocation of attention is restricted to serial processing of objects/words after a preattentive parallel processing stage. Even though SAS models were first developed

for eye movements during reading, the class of models has been extended to a number of other tasks. Thus far, SAS mechanisms have been proposed for scene perception (Henderson, 1992; Rayner & Pollatsek, 1992), visual search (Salvucci, 2001; Williams & Pollatsek, 2007), driving, arithmetic (both by Salvucci, 2001), and most recently in a number of search-like scanning tasks (Reichle et al., 2012).

Across tasks, SAS models can be defined by two principles related to attention allocation and saccade programming. First, processing is limited to a single stimulus and after completion of a certain processing stage attention shifts from the currently processed stimulus to the next. Within a task, attention shifts are always triggered by the same processing event as lexical access of the attended word during reading (Reichle et al., 1998) or deciding whether a target is present within the fixated area during visual search (Becker & Williams, 2011; Rayner, 1995). Second, saccade programs are either initiated in synchrony with an attention shift towards the next stimulus (Engbert & Kliegl, 2001; Heinzle et al., 2010; Reichle et al., 2012; Salvucci, 2001) or are programmed towards the next stimulus while processing of the current stimulus is in a final stage (Reichle et al., 1998).

Recently, Reichle et al. (2012) used the E-Z Reader model to investigate the eye-mind link in 1-D scanning tasks (target word search, z-string reading, and Landolt-'C' search) and emphasized the distinctive role of eye-movement control in reading. According to their simulations, saccades and attention shifts are programmed in synchrony during scanning tasks, while initiation of a saccade program towards the next word preceded attention shifts during reading. Furthermore, the authors concluded that the SAS mechanism seems flexible enough to guide eye movements in tasks other than reading.

Since eye movements are closely related to the serial progression of attention a number of hypotheses can be derived for SAS models across tasks. First, due to the attentional shift operation, properties of upcoming stimuli do not influence fixation durations. In contrast, parafoveal-on-foveal (PoF) effects, defined as the modulation of fixation durations by the next word/stimulus, have been reported during reading (e.g. Kliegl et al., 2006) and visual search (Williams & Pollatsek, 2007; Trukenbrod & Engbert, 2014, in press; but see Rayner, Pollatsek, et al., 2007, and Kliegl, 2007, for a discussion of PoF effects). Since PoF effects are generally stronger when fixations are close to the next word/stimulus, saccadic undershoots have been suggested as the main cause for PoF effects (Drieghe, 2008; Williams & Pollatsek, 2007). From this perspective, PoF effects arise from mislocated fixations that were intended to fixate the next word/stimulus. Here we suggest to examine refixation behavior in order to minimize the role of mislocated fixations when analyzing PoF effects. Both the decision to refixate and the fixation duration prior to a refixation are determined before attention moves away from the fixated stimulus. Interestingly, this assumption is also true for the decision to move to the next stimulus. Thus, even if a refixation results from a saccadic undershoot in SAS models, the decision was based on the refixated item.

Second, according to SAS models saccades will be directed towards attended or soon-to-be-attended stimuli. Hence, stimulus elements beyond the next saccade target have not yet been in the focus of attention and cannot influence target selection or fixation durations. The existence of long-range modulations, that is, the farthest stimulus that

affects eye movements is significantly different from the next saccade target, contradicts sequential attention shifts as the basis of eye-movement control.

Third, SAS models predict increased fixation durations before skipping saccades. Skipping costs inevitably arise in SAS models due to the cancelation of a saccade program to stimulus $n + 1$ and the initiation of a new saccade program to stimulus $n + 2$. Saccade cancelation and initiation are time-consuming and induce prolonged fixation durations prior to skipplings. Hence, the observation of skipping benefits, that is, reduced fixation durations before skipplings, is incompatible with the SAS framework. Both skipping costs (Pollatsek, Rayner, & Balota, 1986; Pynte, Kennedy, & Ducrot, 2004; Rayner, Ashby, Pollatsek, & Reichle, 2004) and skipping benefits have been reported in reading experiments (Drieghe, Brysbaert, Desmet, & De Baecke, 2004; Radach & Heller, 2000). Following a corpus analysis, Kliegl and Engbert (2005) suggested word length (or word frequency) as the mediating factor, since skipping costs arose before skipping of long (or low-frequency) words, while skipping benefits arose before skipplings of short (or high-frequency) words.

The rationale behind the experimental paradigm studied here was to check the compatibility of serial processing as the basis of eye movement control in a serial task. Our approach is based on a sequential scanning task in which each stimulus informs about the position of the next task-relevant stimulus (Trukenbrod & Engbert, 2007; see also Hooge & Erkelens, 1998; Greene & Rayner, 2001). Participants were instructed to identify a path embedded into a display of Landolt-'C's (Fig. 3.1). Gaps of Landolt-'C's pointed towards the next stimulus in a sequence. A trial started with a highlighted stimulus. In the example, the gap of the first stimulus is on the right side and points towards the next stimulus to the right. The next two stimulus elements also point rightwards. A sequence ends on a target symbol consisting of a stimulus with four gaps. According to SAS models, participants need to recognize the orientation of the gap in the currently fixated Landolt-'C' before attention can be shifted towards the next stimulus.

3.2 Method

3.2.1 Participants

Thirty students of the University of Potsdam participated in an experiment consisting of two blocks tested in separate sessions. Data from one block are reported in this study. In the other block, the same type of stimulus material was used with a different instruction. Sessions lasted about one hour and blocks were counterbalanced across participants. All subjects reported normal or corrected-to-normal vision and received study credits or were paid 10€ for participation.

3.2.2 Procedure and materials

Participants performed 50 trials consisting of sequences containing 52 to 55 symbols. Each sequence was embedded into a square display of 18×18 aligned symbols (Fig. 3.1). Stimulus elements were black Landolt-'C's (size: 0.86° when presented centrally, line width: 0.18°) with a gap (size: 0.23°) in one of four cardinal positions (0° , 90° , 180° , 270°) presented on a light gray background. Stimulus elements were placed on an invisible grid

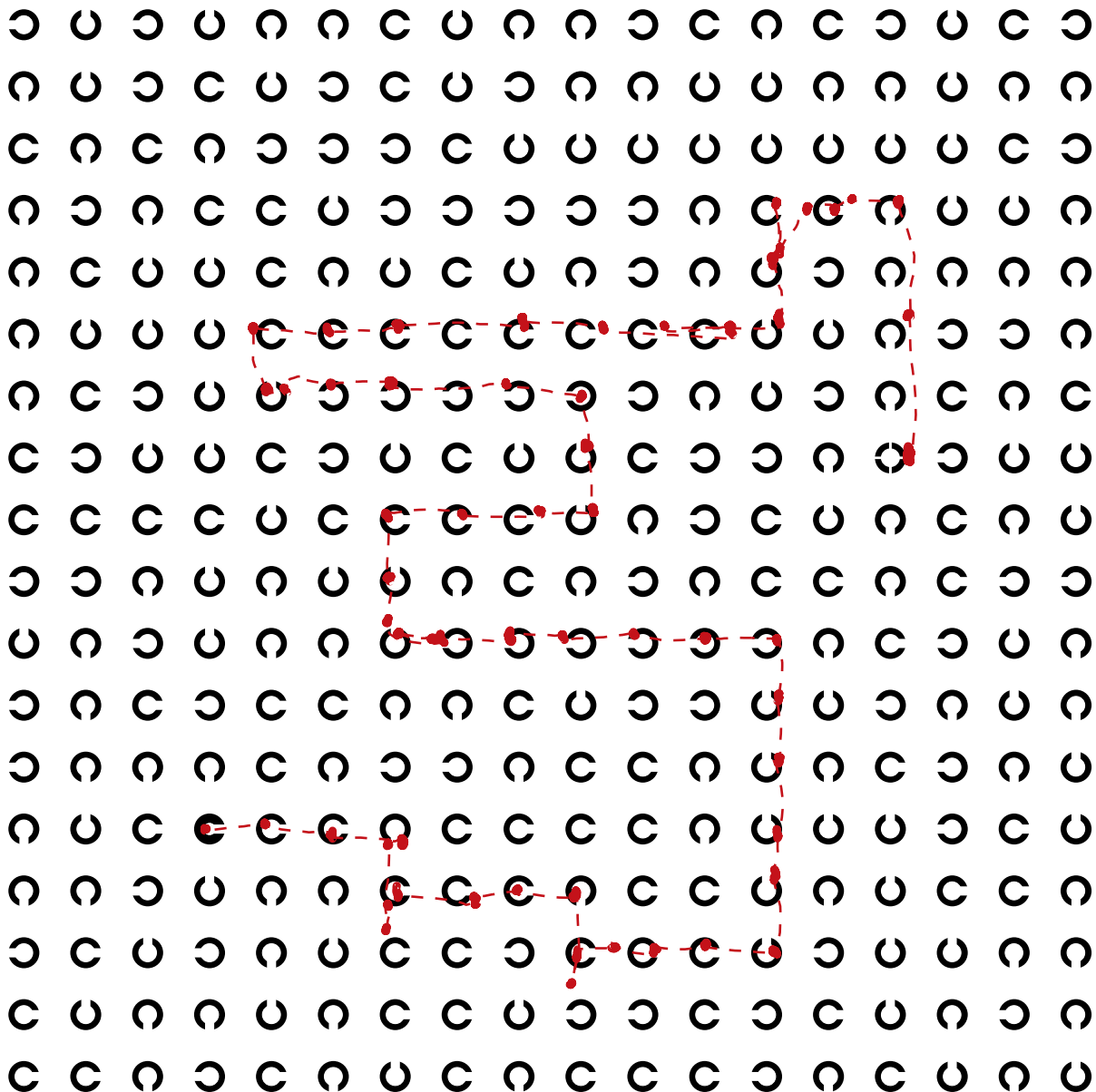


Figure 3.1: Example for the display in the sequential search task. Participants were instructed to follow a path of Landolt-Cs. The gap of each stimulus element indicates the movement direction to the next symbol. The sequence started on a bold symbol, the target consisted of a ring with four gaps. A typical eye-movement sequence is plotted by the line trace.

with a distance of 1.73° between stimulus centers resulting in a quadratic arrangement of 30.21° width. The first stimulus element in a sequence was presented with a bold line (0.27°). Gaps of Landolt-'C's pointed to the position of the next stimulus. Participants scanned each sequence until they found a target stimulus, which was a ring with four small gaps (size: 0.05°).

3.2.3 Eye movement recording and data preprocessing

We recorded eye movements using the EYELINK-II system (SR Research, Osgoode, ON, Canada) with a sampling rate of 500 Hz and an instrumental spatial resolution of less than 0.01° . Participants were seated 50 cm in front of a 21-in. Iiyama Vision Master Pro

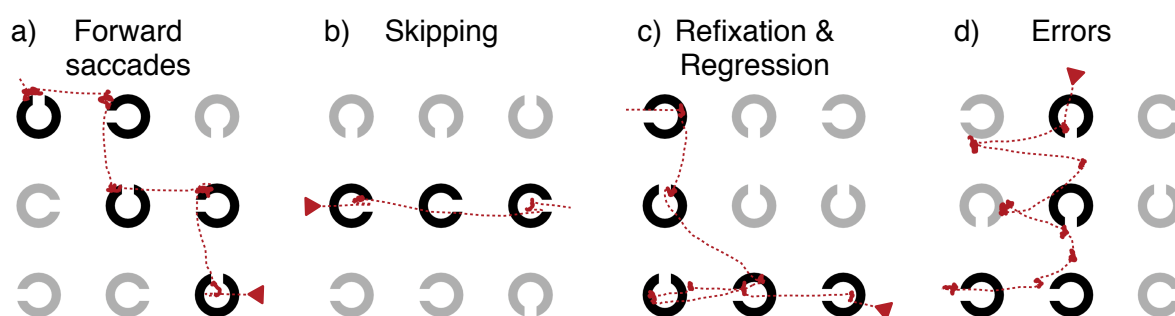


Figure 3.2: Illustration of different saccade types. Stimulus elements on the path are plotted in black, gray stimulus elements represent distractors. Average eye position is drawn with a red line where dashed parts represent saccades and solid lines represent fixations, respectively. (a) Forward saccades; (b) skipping saccade; (c) refixation and regression; (d) erroneous saccades. Red arrows indicate movement direction of eye traces in each example.

514 CRT monitor (1024×768 resolution, refresh rate 100 Hz) with their head on a chin rest to reduce head movements. Stimulus presentation and response collection were controlled by an Apple G3 computer and implemented in MATLAB (The MathWorks, Natick, MA, USA) using the Psychophysics (Brainard, 1997; Pelli, 1997) and Eyelink (Cornelissen et al., 2002) toolboxes.

Saccades were detected using a velocity-based algorithm (Engbert & Mergenthaler, 2006) with a relative velocity threshold of 5 standard deviations, a minimum duration of 6 data samples, and minimum amplitude of $1/3$ symbol size. For each fixation, we calculated a mean position averaged across both eyes and assigned it to the closest symbol. Poorly calibrated trials, fixations on the first and the last symbol as well as fixations/saccades containing blinks were excluded from further analyses. All results are based on first-pass scanning of the sequence. Eye movements after saccadic errors and regressions were excluded from further analysis until participants inspected a previously unexplored part of the sequence. Overall, 48,419 fixations remained for further analyses.

3.2.4 Eye-movement classification

Examples of different saccade types are plotted in Figure 3.2. Symbols belonging to the path are plotted in black, distractors in gray. Single fixations in Figure 3.2a are connected by forward saccades from the currently fixated stimulus n to the next stimulus $n + 1$. Figure 3.2b displays an immediate saccade from stimulus n to stimulus $n + 2$, that is, a skipping. A refixation followed by a regression is depicted in Figure 3.2c. After fixating the stimulus in the lower left, a second saccade changes the fixation position within the stimulus n . Subsequently the eyes move back to a previously inspected stimulus $n - 1$. Finally, Figure 3.2d shows saccades that move the eyes away from the sequence. In this example, two distractors are fixated in close succession.

3.3 Results

A representative eye trajectory is displayed in Figure 3.1. Participants scanned the embedded sequences of Landolt-'C's. Fixations were typically located on stimuli belonging to

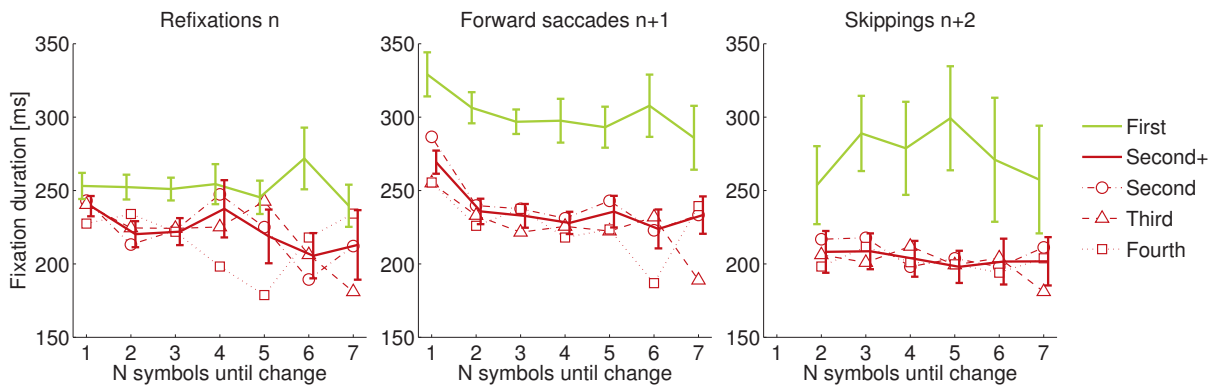


Figure 3.3: Fixation durations. The influence of the next direction change on fixation durations is plotted as a function of the distance to the next stimulus pointing into a direction different from the current movement direction. Fixation durations of refixations, forward saccades, and skippings are shown for saccades executed from the first stimulus (green lines), second to fourth stimulus (red dashed lines), and averaged across saccades executed from second to fourth stimulus (red solid lines).

the path. First-pass analysis revealed that most saccades were directed towards the next symbol $n + 1$ (forward saccades: 62%) or changed the fixation position within a fixated stimulus n (refixations: 19%). Participants occasionally skipped over the next stimulus $n + 1$ and moved immediately to a more distant stimulus $n + 2$ (skippings: 9%) or moved backwards to symbol $n - 1$ (regressions: 3%). A small fraction of fixations was placed on distractors outside of the required sequence (errors: 5%). All others cases were negligible.

3.3.1 Fixation durations

In a first step, we analyzed the effect of upcoming stimuli on fixation durations. Distance of the next direction change was determined within straight segments of Landolt-'C's and was computed as the remaining number of stimuli pointing into the same direction. Fixation durations before refixations, forward saccades, and skippings are plotted in Figure 3.3. Durations of fixations on the first stimulus of a segment (green lines) were longer than fixations on later stimulus elements (red lines). Since fixation durations were very similar after fixation of the first stimulus in a segment, we calculated average fixation durations (solid red lines) from the second to fourth stimulus (dashed red lines). In line with a possible *parafoveal-on-foveal* effect, we observed longer fixation durations before all forward saccades and before refixations on the second to fourth stimulus, if the next symbol $n + 1$ pointed into a new direction. As argued earlier, according to SAS models fixation durations before refixations are least affected by mislocated fixations. Hence, the observed modulations before refixations can be interpreted as strong evidence against eye guidance by sequential attention shifts in this type of task. More distant direction changes, however, had no additional effect on fixation durations.

We statistically validated this observation by computing a linear mixed model for log fixation durations using the *glmer* function of the *lme4* package (Bates & Maechler, 2010) implemented in the R system for statistical computing (version 2.12.0; R Development Core Team, 2010) under the GNU General Public License (version 2, June 1991). Helmert contrasts were used to estimate the influence of distance on fixation durations (Table 3.1). In summary, we observed substantial support for *parafoveal-on-foveal* effects, that

Table 3.1: Helmert contrasts testing long-range modulations. The table shows estimated coefficient, standard error, and t-value of the specified contrasts computed with a general linear mixed model for the log fixation durations of refixations, forward saccades, and skippings. Except for the intercept, contrasts compare fixation durations on the n th stimulus before a change with fixation durations on stimulus elements further away from the change ($> n$). Reliable differences ($t > 3$) are highlighted with bold font.

| Saccade type | First | | | Second+ | | |
|-------------------------|---------------|--------------|---------------|---------------|--------------|---------------|
| | Estimate | SE | t | Estimate | SE | t |
| Refixations | | | | | | |
| (Intercept) | 5.4262 | 0.026 | 208.39 | 5.3164 | 0.027 | 194.01 |
| 1 vs. 2-7 | 0.0005 | 0.002 | 0.25 | 0.0119 | 0.003 | 4.29 |
| 2 vs. 3-7 | 0.0013 | 0.003 | 0.50 | 0.0045 | 0.004 | 1.07 |
| 3 vs. 4-7 | 0.0010 | 0.004 | 0.29 | 0.0025 | 0.007 | 0.38 |
| 4 vs. 5-7 | 0.0026 | 0.006 | 0.42 | 0.0097 | 0.011 | 0.88 |
| 5 vs. 6-7 | 0.0050 | 0.011 | 0.45 | 0.0273 | 0.020 | 1.33 |
| 6 vs. 7 | 0.0485 | 0.022 | 2.17 | -0.0488 | 0.045 | -1.09 |
| Forward saccades | | | | | | |
| (Intercept) | 5.5138 | 0.021 | 262.22 | 5.3845 | 0.021 | 250.86 |
| 1 vs. 2-7 | 0.0083 | 0.001 | 6.05 | 0.0138 | 0.001 | 14.50 |
| 2 vs. 3-7 | 0.0028 | 0.002 | 1.54 | 0.0022 | 0.001 | 1.60 |
| 3 vs. 4-7 | -0.0014 | 0.003 | -0.55 | 0.0009 | 0.002 | 0.44 |
| 4 vs. 5-7 | 0.0061 | 0.004 | 1.42 | -0.0052 | 0.003 | -1.49 |
| 5 vs. 6-7 | 0.0075 | 0.008 | 0.97 | 0.0014 | 0.006 | 0.22 |
| 6 vs. 7 | -0.0077 | 0.016 | -0.49 | -0.0116 | 0.014 | -0.82 |
| Skippings | | | | | | |
| (Intercept) | 5.3069 | 0.032 | 166.83 | 5.2645 | 0.027 | 198.33 |
| 2 vs. 3-7 | 0.0077 | 0.007 | 1.10 | 0.0004 | 0.002 | 0.17 |
| 3 vs. 4-7 | 0.0150 | 0.008 | 1.90 | 0.0023 | 0.003 | 0.85 |
| 4 vs. 5-7 | 0.0321 | 0.013 | 2.54 | 0.0036 | 0.004 | 0.87 |
| 5 vs. 6-7 | 0.0596 | 0.022 | 2.70 | 0.0048 | 0.007 | 0.67 |
| 6 vs. 7 | 0.0355 | 0.046 | 0.77 | -0.0073 | 0.015 | -0.48 |

is, a reliable influence of the next stimulus $n + 1$ on the current fixation duration before refixations on the second to fourth stimulus and before all forward saccades (highlighted in bold font, all $t \geq 3$). Interestingly, the control of fixation durations was primarily limited to stimulus elements close to fixation, since our analyses revealed no or only weak evidence for reliable long-range modulations of fixation durations (all $t < 3$).¹

3.3.2 Target selection

Due to the architecture of SAS models, upcoming objects are expected to influence target selection only if attended. Hence, modulations are restricted to stimuli in close proximity to the next saccade target. In order to test this hypothesis, we analyzed the effect of distance of the next direction change on the proportion of refixations, forward saccades, and skippings analogous to the previous analyses (Fig. 3.4). While distance had almost no effect on the proportion of refixations, forward saccades, and skippings executed from

¹We are aware that $t > 2$ is commonly interpreted as a reliable influence. Due to the problem of multiple comparisons, however, we chose to interpret values of $t < 3$ as weak or no evidence.

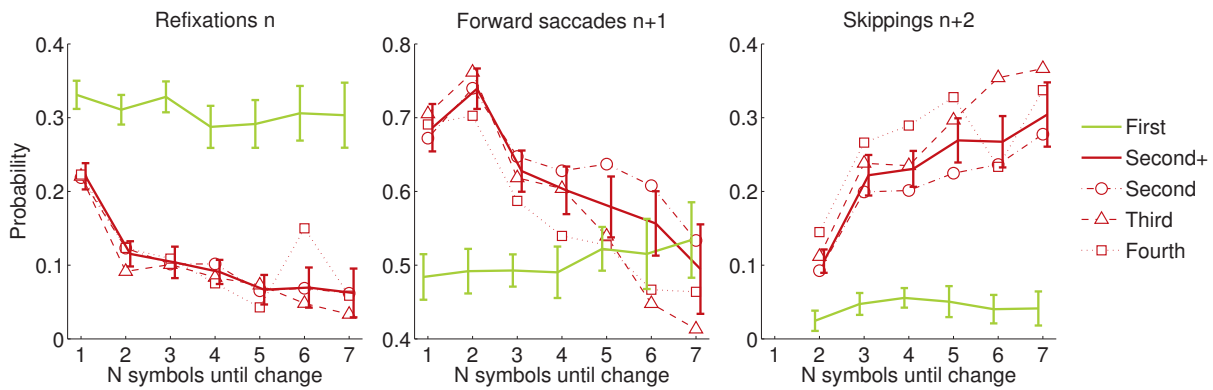


Figure 3.4: Target selection. The influence of the next direction change on target selection is plotted as a function of the distance to the next stimulus pointing into a direction different from the current movement direction. Probabilities of refixations, forward saccades, and skippings are shown for saccades executed from the first stimulus (green lines), second to fourth stimulus (red dashed lines), and averaged across saccades executed from second to fourth stimulus (red solid lines).

the first stimulus in a sequence (green line), distance had a major impact on saccades from the second to fourth stimulus (red line). For statistical inference, we computed a logistic linear mixed model using the *glmer* function of the *lme4* package (Bates & Maechler, 2010) implemented in the R system for statistical computing (version 2.12.0; R Development Core Team, 2010). In line with SAS models, target selection on the first stimulus was rather locally determined. Only stimulus elements close to the saccade target modulated target selection. However, contrary to predictions of SAS models, Helmert contrasts confirmed reliable long-range modulations of refixations, forward saccades, and skippings extending up to at least five stimulus elements for saccades executed from the second to fourth stimulus in a sequence (Table 3.2).² Hence, distant stimulus elements have a strong influence on local eye-movement behavior.

3.3.3 Skipping benefits

Finally, we compared mean fixation durations before forward saccades and skippings averaged across participants. Instead of the skipping costs predicted by SAS models, we observed skipping benefits, that is, a reduction of fixation durations before saccades that induce skippings of stimulus elements (Table 3.3). Fixation durations decreased by 37 ms, $t(29) = 14.29$, $p < 0.001$. Since fixation durations might interact with the sequence of fixations, we restricted the analysis to a subset of fixations in a second analysis (see also Kliegl & Engbert, 2005). First, to ensure local similarity we selected single fixations on a stimulus element. Second, to increase similarity of compared fixation sequences we restricted our analysis to fixations that were preceded and followed by single fixations. Thus, we analyzed the central fixation duration in a triplet of single fixations. Skipping benefits persisted even for these selection criteria, $t(29) = 9.13$, $p < 0.001$ (Table 3.3).

In order to see whether skipping benefits are robust across different movement directions, we further divided the triplets according to the movement direction of the upcoming saccade (Table 3.4). Numerically, we observed skipping benefits for all saccade

²Due to multiple comparisons, we chose to interpret $p > 0.01$ as only weak or no evidence.

Table 3.2: Helmert contrasts testing long-range modulations. The table shows estimated coefficient, standard error, z-value, and p-value of the specified contrasts computed with a logistic linear mixed model for the likelihood of refixations, forward saccades, and skippings. Except for the intercept, contrasts compare saccade probabilities on the n th stimulus before a change with saccade probabilities on stimulus elements further away from the change ($> n$). Reliable differences ($p < 0.01$) are highlighted with bold font.

| | First | | | | Second+ | | | |
|-------------------------|---------------|--------------|---------------|------------------|---------------|--------------|---------------|------------------|
| | Estimate | SE | z | p | Estimate | SE | z | p |
| Refixations | | | | | | | | |
| (Intercept) | -1.082 | 0.064 | -16.95 | <0.001 | -2.406 | 0.084 | -28.76 | <0.001 |
| 1 vs. 2-7 | 0.016 | 0.006 | 2.77 | 0.006 | 0.155 | 0.008 | 19.92 | <0.001 |
| 2 vs. 3-7 | 0.008 | 0.008 | 0.98 | 0.325 | 0.076 | 0.012 | 6.46 | <0.001 |
| 3 vs. 4-7 | 0.021 | 0.011 | 2.01 | 0.044 | 0.072 | 0.018 | 3.93 | <0.001 |
| 4 vs. 5-7 | -0.008 | 0.018 | -0.45 | 0.649 | 0.054 | 0.031 | 1.75 | 0.080 |
| 5 vs. 6-7 | -0.020 | 0.032 | -0.62 | 0.534 | -0.005 | 0.057 | -0.09 | 0.925 |
| 6 vs. 7 | 0.019 | 0.065 | 0.30 | 0.767 | 0.081 | 0.124 | 0.65 | 0.516 |
| Forward saccades | | | | | | | | |
| (Intercept) | 0.188 | 0.078 | 2.40 | 0.016 | 0.450 | 0.052 | 8.60 | <0.001 |
| 1 vs. 2-7 | -0.004 | 0.005 | -0.86 | 0.388 | 0.068 | 0.005 | 15.00 | <0.001 |
| 2 vs. 3-7 | 0.003 | 0.007 | 0.37 | 0.710 | 0.126 | 0.007 | 18.84 | <0.001 |
| 3 vs. 4-7 | -0.005 | 0.009 | -0.49 | 0.622 | 0.058 | 0.010 | 5.90 | <0.001 |
| 4 vs. 5-7 | -0.010 | 0.016 | -0.62 | 0.534 | 0.074 | 0.016 | 4.69 | <0.001 |
| 5 vs. 6-7 | 0.010 | 0.029 | 0.35 | 0.727 | 0.094 | 0.028 | 3.38 | 0.001 |
| 6 vs. 7 | 0.043 | 0.058 | 0.75 | 0.453 | 0.093 | 0.060 | 1.55 | 0.122 |
| Skippings | | | | | | | | |
| (Intercept) | -2.949 | 0.136 | -21.76 | <0.001 | -1.219 | 0.084 | -14.48 | <0.001 |
| 2 vs. 3-7 | -0.139 | 0.017 | -8.30 | <0.001 | -0.176 | 0.008 | -20.89 | <0.001 |
| 3 vs. 4-7 | -0.039 | 0.019 | -2.02 | 0.044 | -0.043 | 0.011 | -3.87 | <0.001 |
| 4 vs. 5-7 | -0.015 | 0.031 | -0.48 | 0.635 | -0.058 | 0.018 | -3.24 | 0.001 |
| 5 vs. 6-7 | 0.054 | 0.054 | 1.00 | 0.318 | -0.045 | 0.031 | -1.45 | 0.147 |
| 6 vs. 7 | -0.221 | 0.113 | -1.95 | 0.051 | -0.103 | 0.066 | -1.54 | 0.123 |

Table 3.3: Mean fixation duration (M) before executing a saccade to the next symbol (forward) or before skipping the next symbol (skipping); Δ denotes the observed skipping costs/benefits. Skipping costs/benefits were computed for the entire set (Prior FD) and a subset with three successive single fixations (Single FD).

| Saccade type | Prior FD | | | Single FD | | |
|--------------|--------------------|--------|--------------------|--------------------|--------|-------------------|
| | M | SE^a | N | M | SE^a | N |
| Forward | 254 | 5.1 | 30119 ^b | 230 | 51.2 | 3500 ^b |
| Skipping | 217 | 5.2 | 4060 ^b | 199 | 5.5 | 560 ^b |
| Δ | -37 ^{***} | 2.6 | 30 ^c | -31 ^{***} | 3.4 | 30 ^c |

* $p < .05$; ** $p < .01$; *** $p < .001$, two-tailed t-Test for paired samples

a) Standard errors (SE) across subjects.

b) Number of observed events.

c) Number of participants with both forward saccades and skippings.

directions. However, for upward movements effects were not statistically reliable, $t(23) = 1.35$, $p = 0.19$ (in all other cases $p < 0.001$). To test whether skipping benefits were compensated by additional processing time during the previous and next fixations, we

3. Distributed processing

Table 3.4: Mean fixation duration (M) before executing a saccade to the next symbol (forward) or before skipping the next symbol (skipping); Δ denotes the observed skipping costs/benefits. Results are based on a subset with three subsequent single fixations on symbol $n1$, n , and $n + 1$ and were divided into cases according to movement direction of saccades.

| Fixation | | Horizontal movement | | | | | |
|----------------------|----------|---------------------|--------|-------------------|-----------|--------|------------------|
| | | Leftward | | | Rightward | | |
| | | M | SE^a | N | M | SE^a | N |
| Single FD $n - 1$ | Forward | 257 | 6.7 | 759 ^b | 243 | 6.9 | 721 ^b |
| | Skipping | 223 | 11.7 | 109 ^b | 243 | 12.3 | 210 ^b |
| | Δ | -34* | 12.3 | 29 ^c | 0 | 11.4 | 30 ^c |
| Single FD n | Forward | 221 | 7.8 | 759 ^b | 204 | 5.5 | 721 ^b |
| | Skipping | 182 | 7.5 | 109 ^b | 178 | 6.0 | 210 ^b |
| | Δ | -39*** | 6.6 | 29 ^c | -26*** | 4.9 | 30 ^c |
| Single FD $n + 1$ | Forward | 235 | 7.5 | 759 ^b | 222 | 7.1 | 721 ^b |
| | Skipping | 248 | 14.5 | 109 ^b | 218 | 8.8 | 210 ^b |
| | Δ | 13 | 13.3 | 29 ^c | -4 | 8.9 | 30 ^c |
| | | Vertical movement | | | | | |
| | | Upward | | | Downward | | |
| | | M | SE^a | N | M | SE^a | N |
| Single FD $n - 1$ | Forward | 247 | 7.0 | 1073 ^b | 277 | 9.2 | 947 ^b |
| | Skipping | 236 | 10.6 | 85 ^b | 257 | 12.5 | 156 ^b |
| | Δ | -11 | 10.6 | 24 ^c | -20 | 11.9 | 29 ^c |
| Single FD n | Forward | 226 | 6.5 | 1073 ^b | 268 | 9.8 | 947 ^b |
| | Skipping | 211 | 11.9 | 85 ^b | 224 | 7.8 | 156 ^b |
| | Δ | -15 | 10.8 | 24 ^c | -44*** | 6.1 | 29 ^c |
| Single FD $n + 1$ | Forward | 235 | 7.5 | 1073 ^b | 273 | 8.2 | 947 ^b |
| | Skipping | 248 | 14.5 | 85 ^b | 257 | 16.3 | 156 ^b |
| | Δ | 13 | 13.3 | 24 ^c | -16 | 14.0 | 29 ^c |

* $p < .05$; ** $p < .01$; *** $p < .001$, two-tailed t-Test for paired samples

a) Standard errors (SE) across subjects.

b) Number of observed events.

c) Number of participants with both forward saccades and skipplings.

inspected the corresponding fixation durations (Table 3.4) and observed no compensatory prolongation of adjacent fixations (all $p > 0.10$).

Finally, in order to control for a possible confounding effect of priming or by statistics of the paths we split our analysis of skipping benefits for different positions within straight segments of the path (Fig. 3.5). Analogous to the previous analyses on long-range modulations, fixation durations are plotted relative to the next direction change for fixations on the first to fourth stimulus in a segment (panels a-d). A linear mixed effect model was estimated for log fixation durations using the *glmer* function of the *lme4* package (Bates & Maechler, 2010). Our analysis revealed a main effect of skipping benefits, longer fixation durations on the first stimulus compared to later stimuli, and a linear trend of distance with longer fixations towards the end of a sequence (Table 3.5). The only reliable interaction revealed that skipping benefits were smaller on the first compared to the second stimulus. All other interactions were statistically not reliable (all $t < 2.00$). In summary, skipping benefits were highly reliable and persisted over different movement directions as well as across different positions within the path.

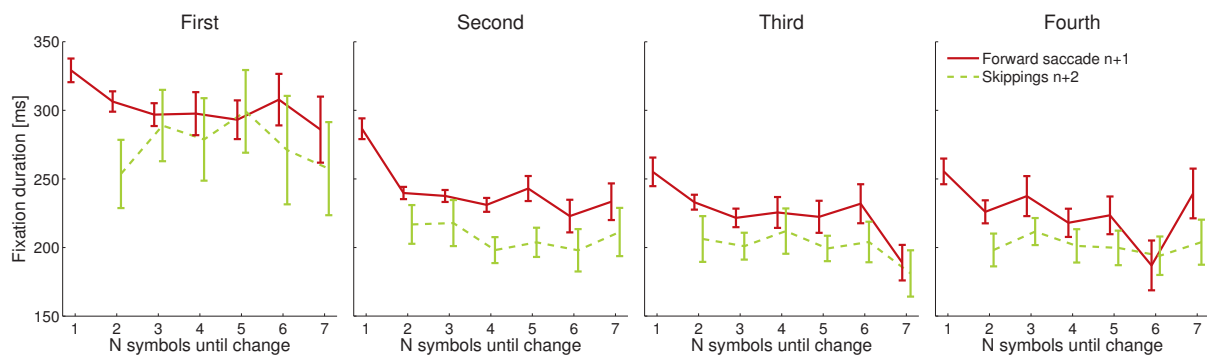


Figure 3.5: Skipping benefits. Fixation durations before forward saccades (red lines) and skippings (green lines) for saccades executed from the first to fourth stimulus in straight segments (panels from left to right). Fixation cases were subdivided into groups according to the next direction change.

3.4 Discussion

We were interested in the question whether eye movements are under control of serial processing of objects in a sequential task. We investigated three critical predictions of sequential attention shift (SAS) models: (i) The absence of parafoveal-on-foveal effects, (ii) the absence of long-range modulations of upcoming stimulus elements, and (iii) the existence of skipping costs. All predictions were refuted for this type of scanning task. First, fixation durations on stimulus n were prolonged by direction changes on the next stimulus $n + 1$. Most critically, the prolongation was also observed before refixations, excluding a possible role of mislocated fixations. Second, proportion of refixations, forward saccades, and skippings were modulated by distant stimuli. Since these stimuli were far away (up to about five stimuli) from the next saccade target (the restricted locus of attention in SAS models), our findings are incompatible with the SAS framework. Third, instead of prolonged fixation durations before skipping saccades, we observed shortened fixation durations. These skipping benefits were stable across movement

Table 3.5: Fixed effects of the linear mixed model. Third-order-interactions were removed from the model (all $t < 2$). The table shows estimated coefficient, standard error, and t-value when comparing log fixation durations before forward saccades and skippings. Reliable effects are highlighted in bold font ($t > 2$).

| | Estimate | SE | t |
|--------------------------------|---------------|--------------|---------------|
| (Intercept) | 5.391 | 0.020 | 269.08 |
| SKB (Skipping Benefits) | -0.104 | 0.008 | -12.75 |
| 1 vs. 2 | -0.063 | 0.011 | -5.63 |
| 1 vs. 3 | -0.151 | 0.013 | -11.42 |
| 1 vs. 4 | -0.132 | 0.015 | -8.65 |
| DTE (Distance to end) | -0.006 | 0.003 | -2.10 |
| DTE x (1 vs. 2) | 0.002 | 0.006 | 0.33 |
| DTE x (1 vs. 3) | -0.010 | 0.008 | -1.20 |
| DTE x (1 vs. 4) | 0.005 | 0.010 | 0.49 |
| (1 vs. 2) x SKB | -0.052 | 0.023 | -2.28 |
| (1 vs. 3) x SKB | 0.007 | 0.027 | 0.27 |
| (1 vs. 4) x SKB | 0.061 | 0.031 | 1.96 |
| DTE x SKB | 0.002 | 0.005 | 0.45 |

directions and persisted when analyses were restricted to selected sequences of fixations. In addition, triplets of single fixations revealed no temporal compensation on preceding or subsequent fixations. Thus, even if skipping benefits resulted from a speed-accuracy tradeoff³, missing compensatory effects on neighboring stimuli indicate that our data are incompatible with the SAS framework.

3.4.1 Distributed processing

In SAS models attention is directed towards single objects. In our analyses, we assumed that individual Landolt-'C's represent the unit of an object. However, objects can emerge from multiple stimuli like words that are composed of multiple letters. In a similar way, segments of several Landolt-'C's, which point into the same direction, might form larger objects. Consequently, one could argue that long-range modulations of saccadic behavior might still be compatible with SAS models if attention is allocated to objects composed of a varying number of elementary Landolt-'C's. While this assumption seems psychologically plausible, we argue that overall eye-movement patterns contradict such an interpretation. Attention allocation to objects formed from multiple stimuli should be visible in saccadic landing positions. Nevertheless, forward saccades aimed at the center of the next Landolt-'C' (see Trukenbrod & Engbert, 2007 for detailed analyses of landing-site distributions).

In saccadic sequences, attention is generally allocated to the location of the next saccade target (e.g., Gersch, Kowler, & Doshier, 2004), while attention allocation to subsequent saccade targets has only been reported infrequently (Baldauf & Deubel, 2008; Godijn & Theeuwes, 2003). In some tasks, this dissociation can be explained by two separate mechanisms (Gersch et al., 2009). While saccade programming facilitates processing at the endpoint of the next saccade, visual layout of the stimulus material boosts processing at subsequent saccade targets. In our experiment, grouping of stimulus elements might indeed support parallel processing of multiple Landolt-'C's, which in turn affects eye guidance. Nonetheless, our results demonstrate that distributed processing influences eye movements in a sequential task and contradict eye guidance that is exclusively based on SAS principles. Interestingly, the current version of E-Z Reader (Reichle, Warren, & McConnell, 2009) assumes an early stage of parallel processing. This stage has been suggested to modulate target selection, but until now the exact interplay has not been specified. Whether an SAS model with a stronger emphasis on parallel processing is able to account for the observed effects remains open to question.

3.4.2 Impact on eye guidance

Two more aspects of our results are worth highlighting. First, immediately after a direction change, target selection is solely influenced by stimulus elements close to fixation. Only on subsequent fixations, processing expands to more distant stimulus elements. Obviously, attention allocation is dynamic, where the reallocation of attention

³Findlay (1995) reported a speed-accuracy tradeoff in an eye movement task. Since skippings are executed after short fixation durations, saccade targets are less precise and might aim at an intermediate position of multiple objects.

is not accomplished immediately, but needs some time to rearrange. In line with this interpretation, Golomb, Pulido, Albrecht, Chun, and Mazer (2010) reported a slow decline of attention at previously attended retinotopic locations. In our task, attention may be allocated to several stimulus elements in straight segments. Immediately after a saccade, attention will be distributed across the retinotopic locations attended prior to the saccade. If the saccade moves the eyes within a straight segment, processing may continue without interruption since the path remains mostly within the attended area. However, after a saccade towards the first stimulus of a segment, most stimulus elements within the attended area are distractors and attention needs time to be reallocated towards the new segment. One prediction of this behavior is the processing of irrelevant symbols. Interestingly, the number of saccadic errors at the end of straight segments is the most frequent error observed in our task.

Second, even though target selection was affected by distant stimulus elements, fixation durations were primarily controlled by stimulus elements close to fixation. Even though a separation between target selection and control of fixation durations has been suggested previously (Findlay & Walker, 1999), the clear distinction suggested by results from our task is important for eye-movement models in general. In particular, it will be interesting to investigate how compatible our results are with models assuming that both decisions of when and where to move the eyes are linked to the same processing event during scanning tasks (Reichle et al., 2012). Hence, the paradigm may be seen as an interesting benchmark for existing models of eye-movement control.

3.4.3 A model of eye-movement control

Our interpretation of the results is based on the SWIFT model (Engbert et al., 2005) and can be summarized by three principles. First, visual input is processed in parallel with faster processing close to fixation. The input progresses through a number of different stages, in which features, objects, and higher-level information is extracted over time. Second, an autonomous timer initiates saccades after random time intervals that may be prolonged by ongoing processing close to fixation. Thus, the temporal decision to initiate a new saccade is not fully determined by a specific processing event (Nuthmann et al., 2010; Trukenbrod & Engbert, 2014, in press). Third, eye-movement targets are computed from a temporally evolving activation field. Since processing of the visual input advances steadily, various factors continuously shape the activation field and respective target-selection probabilities. Interestingly, model simulations with SWIFT demonstrate that these principles generate skipping benefits during reading (Engbert & Kliegl, 2011) and scanning tasks (Trukenbrod & Engbert, 2014, in press). The compatibility with long-range interactions and parafoveal-on-foveal effects, however, still needs to be demonstrated.

3.5 Conclusions

Model generalizability is a key concept in model evaluation, analysis, and comparison (Pitt et al., 2002). Using a sequential search task, we present experimental results incompatible with the SAS mechanism in a non-reading task. Thus, while the SAS framework might

represent a useful approximation of the cognitive processing underlying certain tasks, such an architecture could turn out to be a special case of a more general cognitive architecture underlying visuomotor behavior. Candidates for this more general framework seem to be based on processing by parallel graded attention.

3.6 Acknowledgments

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Chapter 4

ICAT: A Computational Model for the Adaptive Control of Fixation Durations

Hans A. Trukenbrod and Ralf Engbert
University of Potsdam, Germany

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Abstract

Eye movements are used to investigate cognitive processes related to visual information processing. Much has been learned about the spatial selection of fixation locations. While most extensively investigated in reading, the principles governing the temporal control (fixation durations) are less clear. Here we review and extend theories of the control of fixation durations in tasks like visual search and scanning, scene perception, and reading to develop a new model for the control of fixation durations. We distinguish two local principles from one global principle of control. First, an autonomous saccade timer initiates saccades after random time intervals (Local-I). Second, foveal inhibition permits immediate prolongation of fixation durations by ongoing processing (Local-II). Third, saccade timing is adaptive, so that the mean timer value depends on task requirements and fixation history (Global). We demonstrate by numerical simulations that our model reproduces patterns of mean fixation duration patterns as well as corresponding distributions in various tasks. When combined with assumptions of saccade-target selection and oculomotor control, the model accounts for both temporal and spatial aspects of eye-movement control. We conclude that the model provides a promising solution to the general problem of fixation duration control in saccadic tasks.

4.1 Introduction

Visual perception is a highly dynamic process during which saccadic eye movements continually scan the environment (Findlay & Gilchrist, 2003). Because of the anatomy of the retina and resulting acuity limitations outside of the foveal region, eye movements are essential for human vision. The generation of saccadic eye movements is based on two largely independent pathways for spatial (*where*) and temporal (*when*) control (Findlay & Walker, 1999). Due to this independence, a research strategy focussing on spatial aspects of saccade generation turned out to be successful, so that, over the last decade, considerable progress was made on the question of how the next saccade target is selected. Most importantly, this research generated detailed computational models that account for the selection of fixation locations during reading (e.g., Engbert et al., 2005; Reichle et al., 1998; Engbert & Krügel, 2010), scene perception (e.g., Itti & Koch, 2001; Kienzle, Franz, Schölkopf, & Wichmann, 2009; Torralba, Oliva, Castelhano, & Henderson, 2006), and visual search (e.g., Najemnik & Geisler, 2005; Rutishauser & Koch, 2007; Zelinsky, 2008).

Contrary to the spatial control of eye movements, control processes, which determine the duration of a fixation, were almost exclusively addressed in eye-movement models in reading (e.g., Engbert et al., 2005; Reichle et al., 1998, 2003, for an overview). To fill this gap Rayner (2009) suggested that experimental paradigms developed to analyze fixation durations in reading should be more widely adopted to other domains of eye-movement research. This research strategy was recently applied to a series of experiments that utilized the stimulus onset delay paradigm (Rayner & Pollatsek, 1981) to analyze the control of fixation durations in scene viewing (Henderson & Pierce, 2008; Henderson & Smith, 2009). Based on these results, Nuthmann et al. (2010) proposed a computational model for the control of eye movements in scene viewing (CRISP), which implemented some of the principles developed in the SWIFT model for saccade generation in reading (Engbert et al., 2005).

In this article, we generalize the computational approach introduced by Engbert et al. (2005) and Nuthmann et al. (2010) and address the problem of fixation duration control from a broader perspective. The starting hypothesis is that fixation durations are controlled on two different levels: (i) Local control depending on processing difficulty of the item in foveal vision affects the current fixation and (ii) global control related to overall task requirements affects fixations over a sustained period and not just single fixations. Current models provide detailed explanations of local control. For example, in reading a low-frequency word consumes more processing time and produces higher fixation durations (Reichle et al., 2003). However, global control is either neglected or only assumed implicitly, even though it constitutes a key mechanism in a number of theories, for example, for the adjustment of fixation durations across tasks (Hooge & Erkelens, 1998). According to our hypothesis of global and local control principles, average fixation durations depend on our previous experience with specific visuomotor tasks and on anticipated processing difficulty. Using mathematical modeling and computer simulations, we investigate the interplay between global and local control. Our approach is in agreement with experimental results on fixation durations derived from different

paradigms and we demonstrate that a limited set of control principles can account for the temporal control of eye movements across tasks.

4.1.1 Global control of fixation durations

Fixation durations range from less than hundred milliseconds to more than a second. Some of this variability is related to global adjustments that affect fixations over sustained periods of time. At least three major sources can be distinguished that cause global adjustments. First, variability is related to global properties of the stimulus material. For example, overall visual clutter in a scene has an impact on fixation durations (Henderson, Chanceaux, & Smith, 2009). Interestingly, local clutter around the point of fixation does not alter fixation durations. In addition, fixation durations are sensitive to visibility of the inspected stimulus. Mean fixation durations increase with decreasing luminance of pictures (Loftus, 1985) and with decreasing contrast during viewing of line drawings (Loftus, 1985), scene perception (Loftus, Kaufman, Nishimoto, & Ruthruff, 1992), visual search (Näsänen, Ojanpää, & Kojo, 2001), and reading (Bowers & Reid, 1997). Low and high pass filtering of an image changes average fixation durations (Groner, Groner, & Mühlennen, 2008; Mannan, Ruddock, & Wooding, 1995). Furthermore, stimulus difficulty modulates fixation durations, which increase with increasing target-distractor similarity (Hooge & Erkelens, 1998; Jacobs, 1986; Vlaskamp, Over, & Hooge, 2005) and increasing complexity of stimulus elements (Gould & Dill, 1969).

Second, task specific processing (Rayner, Li, Williams, Cave, & Well, 2007) affects average fixation durations that last about 225 to 250 ms during reading, 275 to 325 ms during scene perception, and 180 to 275 ms during visual search (for a review see Rayner, 2009). These modulations do not solely depend on stimulus properties and remain when the same stimulus material is viewed under differing instructions. During scene perception, fixations are longer when memorizing a scene in comparison to searching the same scene (Henderson et al., 1999; but see Castelano, Mack, & Henderson, 2009). During reading, average gaze durations decrease when skimming a text (Just & Carpenter, 1987) or repeatedly reading the same text (Hyönä & Niemi, 1990) and lengthen during elaborate processing (Bohn & Kliegl, 2007) and proof-reading (Wotschack, 2009). Similarly, fixation durations increase with memory load during visual search (Gould, 1973).

Third, large interindividual differences are observed in fixation durations. To some degree these differences can be linked to practice. Reading fixations shorten from first to sixth grade (McConkie et al., 1991) and old and young readers use different strategies while reading a text (Rayner et al., 2011). Interindividual differences persist across tasks revealing the tendency of a preferred average fixation duration in participants (Castelano & Henderson, 2008; Rayner, Li, et al., 2007). According to our hypothesis, enduring modulations of fixation durations are the result of an adjustment of global control strategies while local control strategies may modify the duration spent on individual fixations.

4.1.2 Theories of local control of fixation durations

Local fixation duration modulations have extensively been investigated. Resulting theories can be classified into three categories which assume control by a cognitive trigger (direct control), indirect control, or mixed control (Rayner & McConkie, 1976; Rayner, 1977; Rayner & Pollatsek, 1981). *Cognitive trigger* theories assume that the decision to move the eyes is solely based on processing of visual input during a fixation. Saccades might be triggered by the decision whether a target is present in the fixated area during visual search (Rayner, 1995), identification of an object in scene perception (Henderson, 1992), or estimation of a word's familiarity in reading (Reichle et al., 1998). For scanning tasks, Reichle et al. (2012) suggested that the trigger to initiate a new saccade program is synchronized with the trigger that shifts attention to the next object.¹ Thus, cognitive trigger theories postulate a tight link between processing and saccade initiation. Due to the triggering mechanism fixation durations are instantaneously adjusted to processing demands at fixated locations and the interpretation is that fixation durations reflect processing during a fixation. Obviously, cognitive triggers are an attractive model for generating hypotheses about the relation between oculomotor control and ongoing cognition.

As an alternative, *indirect control* theories assume that the control of fixation durations cannot be limited to processing of the fixated region. The motivation for this claim is that average fixation durations range from 200 to 300 ms, a time window, which might be too short for the control of fixation durations by a cognitive trigger. First, because of saccadic suppression, visual input is reduced during the first 35 ms of a fixation (Volkman, Schick, & Riggs, 1968). Second, due to the eye-brain lag, visual input needs at least 50 ms to be transmitted from the retina to the cortex (Fowe & Simpson, 2002; Lamme & Roelfsema, 2000; Poghosyan & Ioannides, 2007). Third, programming of saccades takes 150 to 175 ms (Rayner, Slowiaczek, Clifton, & Bertera, 1983; Rayner, 1998; note that Schall & Thompson, 1999, give slightly smaller estimates of 100 to 150 ms). While processing may continue in parallel with the programming of a saccade, the decision of a cognitive trigger has to be based on the information available beforehand. From these physiological restrictions, a very short time interval is available for cognition to trigger saccade programming and even if cognitive trigger theories are an adequate approximation of saccade generation, decisions to move the eyes would be based on partial knowledge about the fixated region.

Contrary to control by cognitive triggers, indirect control suggests no link between processing and saccade initiation. Instead, saccades are triggered after random time intervals (Hooge & Erkelens, 1998; Kolers, 1976). The mean duration of this autonomous process is adjusted to match task demands, but is not influenced by processing of the fixated area. Thus, indirect control theories assume that the average fixation duration depends on adjustments by global control. Obviously, such a theory is supported by the well-established empirical observation that additional processing time is predominantly acquired by refixations and not by prolongation of the current fixation (Rayner, 2009).

¹More complex variants are conceivable where saccades are triggered by processing beyond the foveal region or by multiple competing processing streams. In this article, we restrict cognitive trigger theories to its simplest form, where saccade programs are initiated by processing of input from the foveated area.

Finally, *mixed control* theories allow influences of the current fixation, but processing is not the sole trigger of saccades. For reading, Henderson and Ferreira (1990) proposed that saccades are initiated when attention moves to the next word or after reaching a deadline independent of current processing (cf., Engbert & Kliegl, 2001). Thus, fixation durations might be controlled by a combination of cognitive trigger mechanisms and indirect control mechanisms. A different class of mixed control theories assumes that fixation durations are primarily terminated by indirect control where processing may prolong the current fixation by inhibiting the execution of the next saccade (Engbert et al., 2005; Feng, 2009; Yang & McConkie, 2001).

4.1.3 Fixations durations across tasks

4.1.3.1 Fixation durations during visual search

Hooge and Erkelens (1996, 1998, 1999) investigated the control of fixation durations in a series of visual search tasks. In a first experiment (Hooge & Erkelens, 1996), mean fixation durations reflected average task demands but durations of single fixations were not adjusted to properties of the fixated stimulus. Instead, saccades were initiated before foveal analysis of the fixated stimulus was completed. This caused a large proportion of saccades to move the eyes away from the target symbol, even though participants were instructed to keep the eyes on the target after an initial fixation. In a second experiment, subject's eyes were guided by foveal information (Hooge & Erkelens, 1998). During this direction-coded search, participants were explicitly instructed to always move the eyes according to the direction given by the fixated stimulus, but a large proportion of fixations was too short to select the correct saccade target. Hooge and Erkelens (1998) concluded that saccades are initiated after random time intervals independent of ongoing foveal processing. In such a random timing model, a mean timer interval is set by a global control mechanism to a value that matches mean processing demands of the foveal (Hooge & Erkelens, 1999) and/or parafoveal analysis (Vlaskamp & Hooge, 2006), while single fixation durations are not adjusted to ongoing foveal processing.

Greene and Rayner (2001) examined eye movements in another direction-coded search task. Different from Hooge and Erkelens' (1996, 1998) displays, the arrangement of stimulus elements by Greene and Rayner (2001) was denser and permitted parafoveal preview of neighboring symbols. As a consequence, Greene and Rayner (2001) observed a higher proportion of correctly directed saccades and argued for a tight link between processing and eye-movement control in dense compared to sparse displays. However, Greene and Rayner (2001) observed a fraction of saccades that were not directed toward the target as predicted by indirect control theories (Hooge & Erkelens, 1998).

Results from both experiments can be explained by indirect control since saccade selectivity depends on the relation between fixation duration and processing. If processing of a stimulus finishes before a saccade is executed, saccades will be directed according to the informative stimulus. However, if a saccade is executed before processing is finished, saccades will be unrelated to the direction prescribed by the stimulus. Since both processing difficulty and specification of the random timer depend on multiple factors like stimulus, preview, and visibility, saccadic performance may vary from unselective to

almost perfectly selective across tasks (see Trukenbrod & Engbert, 2007, for a direction-coded search task with even higher saccade selectivity). In line with this interpretation, saccades in visual search have been shown to be more selective after long fixation durations than after short fixations (Hooge & Erkelens, 1999).

Contrary to indirect control, some studies observed immediate fixation duration modulations during visual search. Fixation durations increase with complexity of stimulus elements (Salthouse & Ellis, 1980) and increasing target-distractor similarity of fixated objects (Becker & Williams, 2011; Trukenbrod & Engbert, 2007; Williams & Pollatsek, 2007). Hence, rejection of distractors has been suggested as the event triggering saccades in visual search (Becker & Williams, 2011; Rayner, 1995).

Recently, Hooge et al. (2007) examined the influence of previously fixated items on later fixations. The most intriguing result was an asymmetry in the control of fixation durations representing a bridge between the seemingly contradictory results. When the preceding fixation was placed on an easy item, fixation durations increased immediately on difficult symbols. In contrast, if the preceding fixation was placed on a difficult stimulus, durations of the next fixation were unaffected by the difficulty of the fixated symbol. Hooge et al. (2007) relaxed the assumption of pure indirect control and proposed a mixed control strategy in visual search. According to this strategy fixation durations are affected asymmetrically by local and global control mechanisms : (i) Immediate prolongations of fixation durations can be seen when processing demands increase (local control), but (ii) decrease only gradually (with a temporal delay) when processing demands decrease (global control).

4.1.3.2 Fixation durations during reading

Control of fixation durations has extensively been investigated during text reading and a number of observations support control by cognitive triggers during reading. Several word properties have been shown to affect fixation durations (for reviews of eye movements in reading see Rayner, 1998, 2009). Printed word frequency (Just & Carpenter, 1980) and predictability (Ehrlich & Rayner, 1981) are two of the most important factors influencing eye-movement behavior at various levels. Both first-fixation durations as well as gaze durations are elevated on low-frequency (Inhoff & Rayner, 1986; Kennison & Clifton, 1995; Kliegl, Grabner, Rolfs, & Engbert, 2004; Rayner & Duffy, 1986) and unpredictable words (Inhoff, 1984; Rayner & Well, 1996; Zola, 1984). Since lexical processing of a word is affected by frequency and predictability, Reichle et al. (1998) suggested lexical access as the cognitive event triggering eye movements during reading.

Several lines of evidence support the notion of a general and fast lexical influence on fixation durations in reading. First, Reingold, Yang, and Rayner (2010) inspected the first of multiple fixations on a word. Even fixation durations before refixations were modulated by frequency (see Rayner, Sereno, & Raney, 1996). Second, inspection of first-fixation durations revealed that frequency (Staub, White, Drieghe, Hollway, & Rayner, 2010; Reingold et al., 2012) and predictability (Staub, 2011) have an effect on the shift of fitted ex-Gaussian distributions as well as corresponding vincentile plots. In addition, frequency altered the skewness of distributions leading to larger frequency effects for long fixation durations. Thus, the entire range of fixation durations reflects lexical processing.

Third, in the *disappearing text paradigm*, where the fixated word disappears or is masked about 60 ms after the onset of a fixation, frequency manipulations modulate fixation durations like in normal reading (Rayner, Liversedge, White, & Vergilino-Perez, 2003; Liversedge et al., 2004; Rayner, Liversedge, & White, 2006; Rayner et al., 2011). Hence, the visual input from the first 60 ms is sufficient to encode all information needed for lexical processing.

Cognitive trigger theories postulate a causal link between linguistic processing and subsequent fixation durations. Thus, saccades should only be triggered after successful lexical processing of a word. Contrary to this, preventing preview of a word prior to its fixation, postpones or weakens word frequency effects, which reappear in later fixation duration measures (Inhoff & Rayner, 1986; Sereno & Rayner, 2000). Without parafoveal preview of words the proportion of fixations unaffected by frequency rises dramatically from about 9% with preview to over 60% without preview (Reingold et al., 2012). Thus, while most fixation durations are influenced by lexical processing under normal reading conditions, the influence of lexical processing diminishes drastically when preview is impeded. Furthermore, Bouma and deVoogd (1974) demonstrated that reading proceeds without interference when a text is presented at a rate not determined by the subject. Thus, word frequency modulates fixation durations, but it is not a particular linguistic processing event that initiates new saccade programs (Deubel, O'Regan, & Radach, 2000). Nevertheless, it is beyond question that lexical processing has an immediate influence on fixation times during normal reading (Reingold et al., 2012).

In line with this interpretation, Yang and McConkie (2001) identified several principles for the control of fixation durations during reading. Participants read paragraphs in a gaze-contingent experiment. On each page, the text was replaced for the duration of one fixation by an alternative stimulus with varying similarity to the original text. In all conditions fixations durations remained highly variable. More importantly, features of the new stimulus differentially affected saccades after short, medium, and long fixation durations. Saccades after short fixations (< 150 ms) remained unchanged in all stimulus conditions. Saccade after medium fixation durations (> 175 ms and < 250 ms) were inhibited when the alternative stimulus disturbed word shape or word boundary information. Only saccades that occurred after long fixation durations (> 275 ms) were inhibited by disruptions of cognitive processing. Similar to fixation duration control in visual search (Hooge et al., 2007), saccades seem to be initiated after random time intervals and may be prolonged by ongoing processing.

Interestingly, an asymmetric fixation duration pattern has also been reported by Kennison and Clifton (1995) in a reading task. While participants read sentences, preview of a target word was prevented. Fixation durations on the target word were analyzed depending on the frequency of the preceding word. After fixating a high-frequency word, fixation durations were affected by word frequency of the target word. Fixations were longer on low-frequency words than on high-frequency words (285 ms vs. 318 ms). In contrast, fixation durations after a fixation on a low-frequency word did not differ between high-frequency and low-frequency words (311 ms vs. 307 ms). Thus, increasing processing demands caused an immediate prolongation of fixation durations, while decreasing processing demands showed no immediate effect. However, until now most

research focused on fixation durations on single words. Systematic manipulations of two or more words are needed to test the assumption of asymmetric control in reading.

4.1.3.3 Fixation durations during scene perception

Control of fixation durations has been rather neglected in scene perception research (Henderson, 2003; Henderson & Hollingworth, 1998; for reviews see Henderson & Hollingworth, 1999; Henderson & Ferreira, 2004). Henderson (1992) proposed a model based on sequential attention shifts to account for eye movements in scene perception. If processing of the foveated object has not proceeded sufficiently before a deadline is reached, a refixation is initiated. Otherwise, as soon as the fixated object is identified, attention moves to the next object and triggers a saccade. In line with this assumption, changing a region during a saccade towards it, prolongs subsequent fixation times even when viewers remain unaware of the change (Henderson & Hollingworth, 2003; M. M. Hayhoe, Bensinger, & Ballard, 1998, for a similar result in a visual working memory task). Similarly, foveal masks presented at the beginning of a fixation prolong the duration proportional to the duration of the mask, while a parafoveal mask presented at the same time has a much weaker effect (Diepen & d'Ydewalle, 2003). Thus, foveal processing seems to be crucial for the control of fixation durations. Furthermore, semantically implausible or inconsistent objects are fixated longer (Friedman & Liebelt, 1981; Loftus & Mackworth, 1978; Henderson et al., 1999). The effect typically shows up in gaze durations by refixating implausible objects more often but is fragile on the level of first-fixation durations (Henderson & Hollingworth, 1998). As an exception, De Graef, Christiaens, and d'Ydewalle (1990) reported differences, which appeared primarily in later stages of scene exploration (i.e., after more than eight fixations).

Asymmetries in the control of fixation durations have not yet been reported for scene perception. However, the control principles discussed for reading (Yang & McConkie, 2001) and visual search (Hooge et al., 2007) provide a coherent way to describe effects on gaze durations as well as individual fixation durations. Modulations of gaze durations are primarily a result of refixations in scene perception (Henderson & Ferreira, 2004) and only rarely reflected in individual fixation durations (Henderson & Pierce, 2008). An indirect control mechanism automatically triggers new saccades (similar to a saccadic deadline, see Henderson, 1992). The eyes move to another object if the foveated object has been processed sufficiently or gain additional processing time through a refixation, if more processing is needed. Furthermore, if processing progresses swiftly, fixations may be immediately prolonged by foveal inhibition. Depending on the exact time course of processing this may result in early modulations of first fixations by syntactic inconsistencies or in late modulations of later fixations by semantic inconsistencies (Vö & Henderson, 2009).

4.1.3.4 Fixation durations in the SOD paradigm

A paradigm with gaze-contingent stimulus presentation (Rayner, 1975) has been used to investigate eye movements during reading (Ishida & Ikeda, 1989; Morrison, 1984; Rayner & Pollatsek, 1981), visual search (Vaughan, 1982; Vaughan & Graefe, 1977),

and scene perception (Henderson & Pierce, 2008; Henderson & Smith, 2009; Shioiri, 1993). At the end of a saccade, the stimulus is replaced by a mask (either a blank screen or an alternative stimulus) and the original stimulus returns after a variable delay. This stimulus-onset delay (SOD) ranged from zero to several hundred milliseconds in experiments. Even though multiple factors varied across experiments (e.g., task, size, and structure of the mask), all experiments revealed a fraction of fixation durations that increased proportionally with the SOD. More importantly, when the analysis was restricted to fixations longer than the SOD, mean fixation durations increased almost perfectly by the amount of the SOD (with a slope of ~ 1 for the relation between SOD and average fixation duration). Thus, a significant proportion of fixation durations is controlled by foveal processing.

The same experiments, however, showed the existence of a second proportion of fixations that were not controlled by processing. As a consequence, multiple modes in fixation duration distributions have been reported in the SOD paradigm (Henderson & Pierce, 2008; Morrison, 1984; Shioiri, 1993). It has been suggested that short fixation durations are pre-programmed during preceding fixations. The number of pre-programmed fixations, however, seems to increase with increasing SOD. For example, Morrison (1984) reported 15 to 30 percent anticipatory saccades when the stimulus was delayed for 200 ms, but 50 to 75 percent for delays of 350 ms. Since pre-programmed saccades are specified during the preceding fixation, the proportion of pre-programmed saccades should not increase with increasing SOD (at least for fixation durations beyond 200 ms).

Even though results from the SOD paradigm have widely been interpreted as evidence for cognitive trigger theories, the existence of a second population of short fixation durations has generally been attributed to a mixed control mechanism (e.g. Henderson & Pierce, 2008; Henderson & Smith, 2009; Rayner & Pollatsek, 1981). In line with this, modeling results of the SOD paradigm are more compatible with the concept of mixed control. Nuthmann et al. (2010) developed the CRISP model based on a random timer with foveal inhibition². While the random timer represents indirect control, foveal inhibition allows modulations of the indirect control mechanism by processing. This mixed-control model, which is in line with the control principles proposed by Hooge et al. (2007), generated two types of saccades (a “pre-programmed” and a “scene-dependent” type) and recovered the two populations of fixations with characteristic mean values and variances.

4.1.4 Core Principles of the model

Mixed control strategies for local control of fixation duration have been demonstrated to provide a viable concept for eye-movement control in both reading (SWIFT: Engbert et al., 2002, 2005) and scene viewing (CRISP: Nuthmann et al., 2010). In both domains, mixed control models consisting of a random timer modulated by processing reproduce complex patterns of mean values and variances of fixation durations. However, indirect control and corresponding modulations need to be adjusted to actual processing needs. Here, we investigate how local strategies are modified by global processing needs. We

²Saccade cancelation was used as an additional process to simulate the pattern of mean values and variances. The role of saccade programming and cancelation in this model will be discussed below.

propose and analyze a framework based on inhibitory control with adaptive timer (ICAT). The fundamental assumption of the ICAT model is that a fine-tuned mixed control mechanism (i.e., a balance of random timing and inhibition) is present in all visuomotor tasks. Such a fine-tuning is essential for the functioning of local control processes, because inhibition can only serve the purpose of processing needs, if the random timer is set to a task-sensitive mean value. Three core principles of fixation duration control interact in the ICAT model. The local principles were previously implemented in SWIFT and CRISP, but interact with an adaptive global control process.

Local-I: Autonomous saccade initiation. Intervals between two subsequent decisions to start saccade programs are generated by a random timer with fixed mean value and standard deviation. This principle provides the main source for the inherent stochasticity.

Local-II: Foveal inhibition. Demanding foveal analysis inhibits the random timer in order to delay the next saccade that terminates the current fixation. Foveal inhibition generates immediate effects of ongoing processing on fixation durations, but is asymmetric, since it only prolongs the current fixation.

Global: Timer adaptation. The mean value of the random timer and the strength of inhibition are modified by processing difficulty experienced during the preceding fixations. For constant processing demands, average fixation durations will be well adapted to processing needs. For varying processing difficulty, the mean value of the saccade timer and the strength of foveal inhibition is updated according to the specific fixation history.

Are all of these principles functional? While principles Local-II and Global are needed to tune the scanning rate of the saccadic system to the cognitive processing difficulty, principle Local-I might be interpreted as a mechanism that randomizes behavior (Carpenter, 1999). Such an interpretation is based on the idea that during the evolution of visuomotor systems, stereotyped responses to upcoming stimuli needed to be avoided, since predictable behavior might have been disadvantageous in predator-prey relations.

Does the random timer concept generalize to other aspects of human motor control? In voluntary interval timing, the random timer concept was introduced by Wing and Kristofferson (1973; see also Vorberg & Wing, 1996). Interestingly, the addition of a stochastic drift process to the timer provided a significant improvement of the Wing-Kristofferson model (Collier & Ogden, 2004). From the perspective developed here, such a stochastic drift can be interpreted as a free-running adaptive mechanisms which generates random modifications to the timer.

4.2 ICAT: A model of saccade initiation intervals

The mathematical formulation of our model is divided into two sections. First, we develop a mathematically rigorous implementation of the ICAT principles. This section is largely independent of (i) oculomotor aspects of saccade generation and of (ii) spatial aspects of saccade target selection. Second, we demonstrate how ICAT can be incorporated into an existing model of eye-movement control to evaluate saccade timing while considering spatial aspects of eye-movement control.

4.2.1 Local-I: A random-walk model of saccade generation

Saccade initiation intervals³ are implemented as a stochastic process, since random-walk models have successfully been used to account for variability of reaction times in behavioral decision processes (Ratcliff, 1978; Smith & Ratcliff, 2004, for a review on two-choice decisions) and eye-fixation durations (e.g., Engbert & Kliegl, 2001; Nuthmann et al., 2010). We assume that a random-walk process (Gardiner, 1990; van Kampen, 1981) with state $n(t)$ at time t , starting from $n(0) = 0$ at time $t = 0$, triggers a new saccade program after reaching a threshold N at the *first-passage time* t_{fp} with $t_{fp} = \min\{t | n(t) = N\}$. In a first step, we implement a one-step process with constant transition probability w over time for a transition from state n to state $n + 1$ and vanishing probability for all other transitions. In this case, the random-walk is a discrete-state, continuous-time *Markov process*, with exponentially distributed waiting times,

$$dt = -\frac{1}{w} \log(1 - \xi), \quad (4.1)$$

where ξ is drawn from independent and identically-distributed pseudo-random numbers with constant probability over the interval $0 \leq \xi < 1$.

The rise-rate to the threshold N is determined by the transition probability \hat{w}_j ,

$$\hat{w}_j = \frac{N}{T_j} \quad (4.2)$$

where N denotes the number of states of the random walk and T_j is the mean duration of the saccade initiation interval j . Note that the mean timer interval T_j remains constant during the entire interval j and adaptive changes of T_j are relatively slow compared to the fast elementary transitions of the random-walk. This separation of time scales provides the basis for the computer implementation of local and global control processes discussed below.

Realizations of the random-walk process are illustrated in Figure 4.1a. The black line highlights a single run. Each random walk consists of multiple elementary steps with durations randomly drawn from an exponential distribution. In most cases, the random walk remains for a short duration in a given state. However, some long durations can be observed. A random walk ends when a pre-defined threshold, the maximum of the discrete state variable $n = N$, is reached. As a result, stochastic fluctuations at the level of elementary transitions produce the variance of fixation durations.

Distributions of saccade initiation intervals (or first-passage times of the random walk) for three different thresholds N are shown in Figure 4.1b. Each distribution consists of 100,000 realizations of the random walk. For all parameter combinations, saccade initiation intervals vary with a pronounced peak at an intermediate duration. Properties of the distribution change with the number of states N . For small N , saccade

³In the first section, we prefer to use the term *saccade initiation intervals* instead of fixation durations, since the control principles of the ICAT model generate durations between two successive saccade initiations without addressing the programming and execution of saccades. In general, fixation durations depend on saccade initiation intervals. The relation, however, is not deterministic and will be illustrated in detail in the next section.

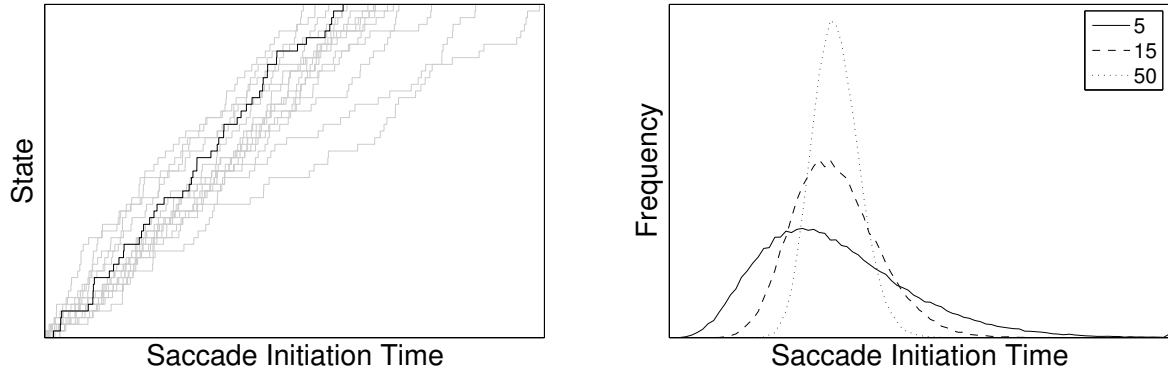


Figure 4.1: Random-walk model for saccade timing. (a) Examples for realizations of the random walk with threshold value $N = 50$. The random walk starts at $n(0) = 0$ and terminates at the threshold value $n(t_{fp}) = N$, which is reached after the first-passage time t_{fp} . (b) Distribution of the relative frequency for three different thresholds $N = 5, 15, 50$. For each distribution 100,000 realizations of the first-passage time t_{fp} were computed.

initiation intervals are more variable and skewed, while large N result in less variable and approximately normal-distributed saccade initiation intervals.

4.2.2 Local-II: Foveal inhibition

According to our second principle, saccade initiation intervals can be prolonged by foveal processing. Foveal processing is represented as an activation $a_f(t)$ that changes over time t . Before processing information content of the foveal region is unknown, after processing the foveal region has been identified. In both cases, foveal activations $a_f(t)$ will have a value of zero. During processing of the foveal region, activations $a_f(t)$ evolve in two stages. In a first stage activations rise to a maximum value A_f , which corresponds to the processing difficulty of the foveated region. In a second stage activations decline until the foveal region is processed. Because cognitive processing can continuously interact with the random walk of the saccade timer, the transition probability is time-dependent,

$$w_j(t) = \hat{w}_j h_j[a_f(t)], \quad (4.3)$$

where $h_j[a_f(t)]$ is the foveal inhibition based on the time-dependent activation $a_f(t)$ in the foveal region⁴ during saccade timer interval j . Throughout the paper, we use a very general form of the inhibition function $h_j[.]$, i.e.,

$$h_j[a(t)] = \exp \left\{ -\alpha \left(\frac{a_f(t)}{A_j} \right)^\beta \right\}, \quad (4.4)$$

where the two free parameters, $\alpha > 0$ and $\beta > 0$, determine the shape of the inhibition function and the expected processing difficulty A_j of timer interval j , which scales the strength of inhibition. Values of the inhibition function $h_j[.]$ range from 0 to 1, so that

⁴Note that, in our model, the maximum of the activation $a_f(t)$ reflects processing difficulty (see Engbert et al., 2005). A more detailed definition of the activation will be given in the next section.

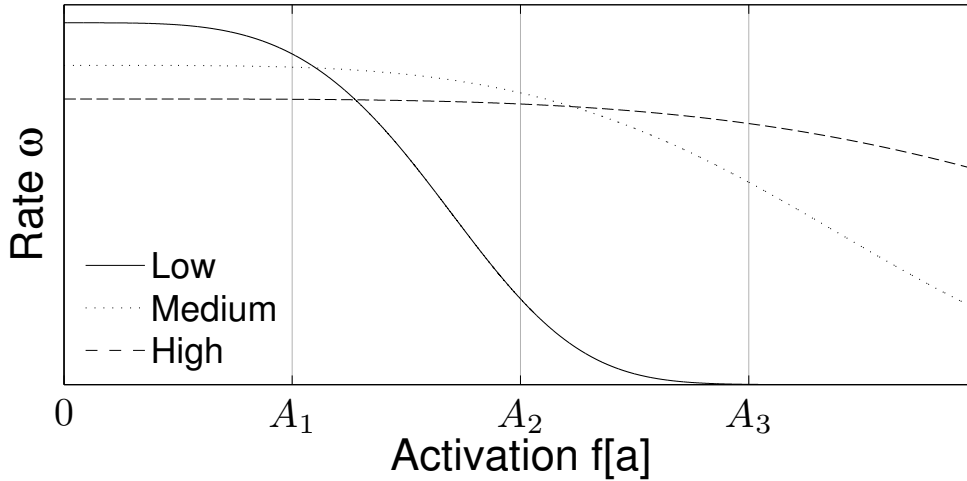


Figure 4.2: Foveal inhibition for three different processing difficulties A_1 , A_2 , and A_3 . For example, given a high foveal activation $a_f \approx A_3$, the strength of the inhibition increases for processing difficulties A_1 to A_3 . Note that the time dependence of $w_j(t)$ is implicit, due to variation of the foveal activation $a_f = a_f(t)$.

foveal inhibition by Eq. (4.3) decreases the transition probability (compared to the baseline \hat{w}) resulting in prolonged intervals of the saccade timer.

Putting together Eqs. (4.3, 4.4), we obtain the time-dependence of the random walk's transition probability,

$$w_j(t) = \frac{N}{T_j} \exp \left\{ -\alpha \left(\frac{a_f(t)}{A_j} \right)^\beta \right\}. \quad (4.5)$$

Modulations of the transition probability by foveal inhibition are illustrated in Figure 4.2. The tail of the inhibition function $h_j[a]$ increases with increasing expected processing difficulty A_j . The solid line illustrates inhibition, when saccade timing is adjusted to a low value A_1 . Foveal activations a_f below A_1 produce only minor modulations. However, when activations exceed the expected processing difficulty, $a_f > A_1$, foveal inhibition decreases considerably. If the expected processing difficulty is much smaller than the actual foveal activation, for example, $a_f > A_3$, the rate drops asymptotically towards zero, $h_3(a_f) \approx 0$. Two additional lines are depicted in Figure 4.2, where foveal inhibition is adjusted to medium processing difficulty A_2 (dotted line) or high processing difficulty A_3 (dashed line). In both cases, activations below the adjusted value produce weak rate modulations, whereas activations exceeding the expected processing difficulty show noticeable inhibition values.

4.2.3 Global: Adjustment of saccade timer

Because the third principle of our model is derived from a different notion than local control of fixation durations, we re-iterate its motivation in short form. There is experimental support (Harris, Hainline, Abramov, Lemerise, & Camenzuli, 1988; Hooge & Erkelens, 1998; Kolers, 1976) for the notion of random timing (Local-I), i.e., saccades are initiated after a random time interval. However, random timers pose the problem of how the mean value of a timer is determined. In general, it is presumed that on average saccades are initiated after a time interval adjusted to overall task demands (Kolers, 1976) or adjusted

to the estimated foveal processing time of previously fixated stimulus elements (Hooge & Erkelens, 1998). Thus, the random timer is based on expected or previously experienced processing difficulty. In the following, we implement the latter principle, since there is experimental support for this concept from visual search tasks (Hooge & Erkelens, 1998).

In the ICAT model, saccade timing is updated gradually after each saccade initiation. Two parameters are affected by this adjustment. First, the time interval j between the initiation of two saccade programs has a predefined average duration T_j . This interval duration increases with increasing processing time of the previous fixations and is set to match the time needed to extract sufficient visual input from the fixated region. Second, the expected processing difficulty A_j reflects the anticipated maximum foveal activation $a_f(t)$ during the next timer interval j . The processing difficulty A_j is needed to scale the strength of foveal inhibition. We assume that both parameters depend on fixation history, which can be formulated as a discrete mapping of the form

$$A_{j+1} = g_A(A_j, A_{j-1}, \dots, A_{j-(d-1)}) \quad (4.6)$$

$$T_{j+1} = g_T(A_{j+1}). \quad (4.7)$$

Thus, change of A_{j+1} represents an autoregressive process of order d defined by the function $g_A(\cdot)$, while the saccade timer interval T_{j+1} is determined by a nonlinear mapping $g_T(\cdot)$ from the actual value of the expected processing difficulty. When the estimation is based on a large number of fixations d , the adaptivity of the timing process will be small and average fixation durations will be relatively stable. Thus, visuomotor tasks with little variation in the mean timing interval are included in our model for $d \rightarrow \infty$.

4.2.4 Qualitative behavior of the saccade timer model

Before we discuss more details of our model of saccade generation, we explore the qualitative behavior of the saccade timing model and investigate the interplay of autonomous saccade initiation, foveal inhibition, and saccade timer adjustments. We use well-defined situations to examine the range of behaviors that can be observed when processing difficulty changes. In each of the presented examples, we illustrate the model's behavior over a sequence of five subsequent saccade initiations, in which processing demands change during the central saccade initiation. We describe single trial simulations and discuss the time-course of average saccade initiation intervals as well as distributions of saccade initiation intervals.

4.2.4.1 Increasing processing demands

In Figure 4.3a we demonstrate the effect of increasing processing demands in a single run of the simulation. Effects can be observed on three levels: On the level of (i) foveal processing, (ii) rate modulations of the random walk, and (iii) the realized random walk. Foveal analysis corresponds to processing during a task and strongly depends on task-specific assumptions. In our model low activations generally indicate low processing difficulty and activations increase with increasing processing demands. High processing demands will generate both high amplitudes of activations as well as long periods of high

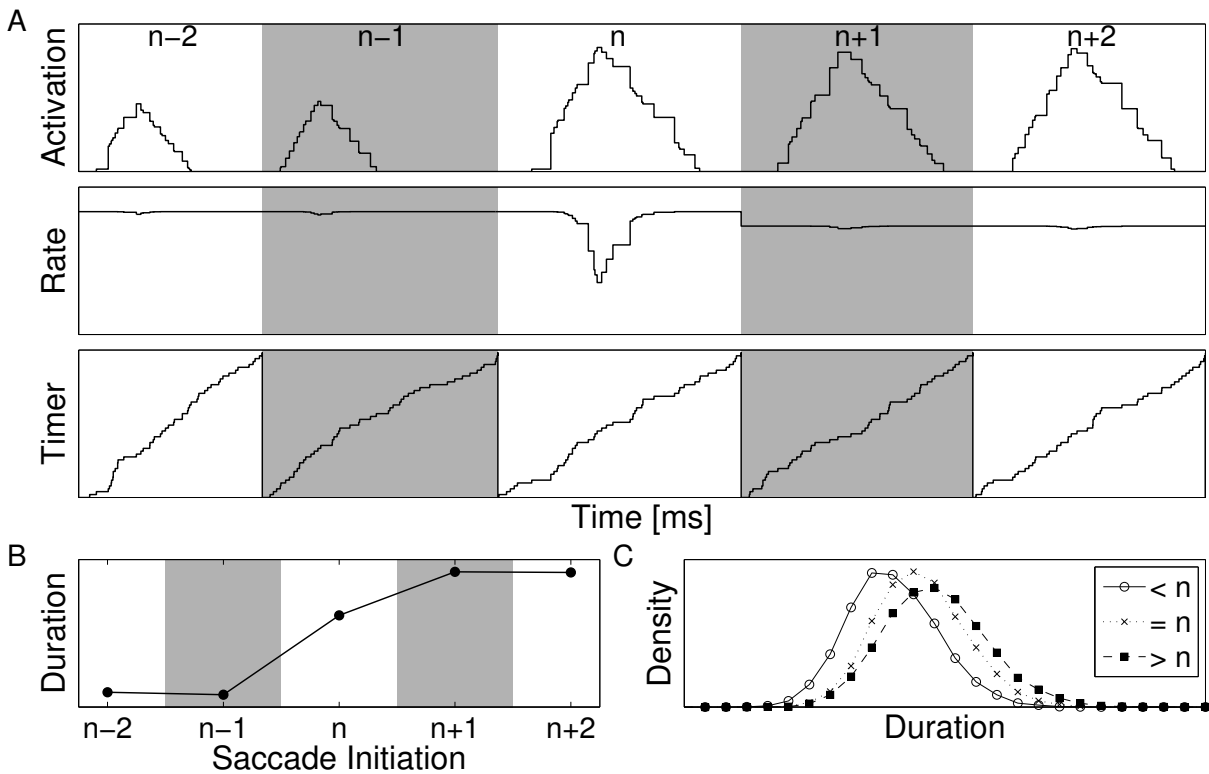


Figure 4.3: Illustration of saccade timer model: Processing demands increase during the n th saccade initiation. Levels of the model: Foveal analysis (top panel), rate modulations (central panel), and the realized random walk (bottom panel). b) Mean saccade initiation intervals before ($< n$), during (n), and after the critical fixation ($> n$). c) Distribution of saccade initiation intervals before ($< n$), during (n), and after the critical fixation ($> n$).

activations. In our example, processing demands are low during the first two saccade initiations ($n - 2, n - 1$), increase during the n th saccade initiation, and remain high on the last two saccade initiations ($n + 1, n + 2$). As a result, activations of foveal processing are relatively small during the first two saccade initiations and increase afterwards (Figure 4.3a, upper panel). Rate modulations are shown in the panel below. Since saccade timing is adjusted to low processing demands, almost no rate modulation is observed during the first two saccade initiations. An increase of processing demands during the n th saccade initiation immediately reduces the rate of the random walk. After adjustment of the saccade timer to higher processing demands at the beginning of saccade initiation $n + 1$, overall rate decreases and modulations by foveal inhibition vanish.

Since each simulation is a stochastic realization of our model, we computed 10,000 simulations using the same parameter combinations to assess overall performance (Fig. 4.3b). Mean saccade initiation intervals are shortest during the first two saccade initiations, where saccade timing is adapted to low processing demands, and longest during the last two saccade initiations, where saccade timing is adapted to high processing demands. When processing difficulties increase during the n th saccade initiation, saccade initiation intervals lengthen on average. For this parameter combination, the prolongation of saccade initiation intervals by foveal inhibition is only a fraction of the increase in saccade initiation intervals observed after re-adjustment of the saccade timer. The distributions are shifted toward mean saccade initiation intervals (Fig. 4.3c).

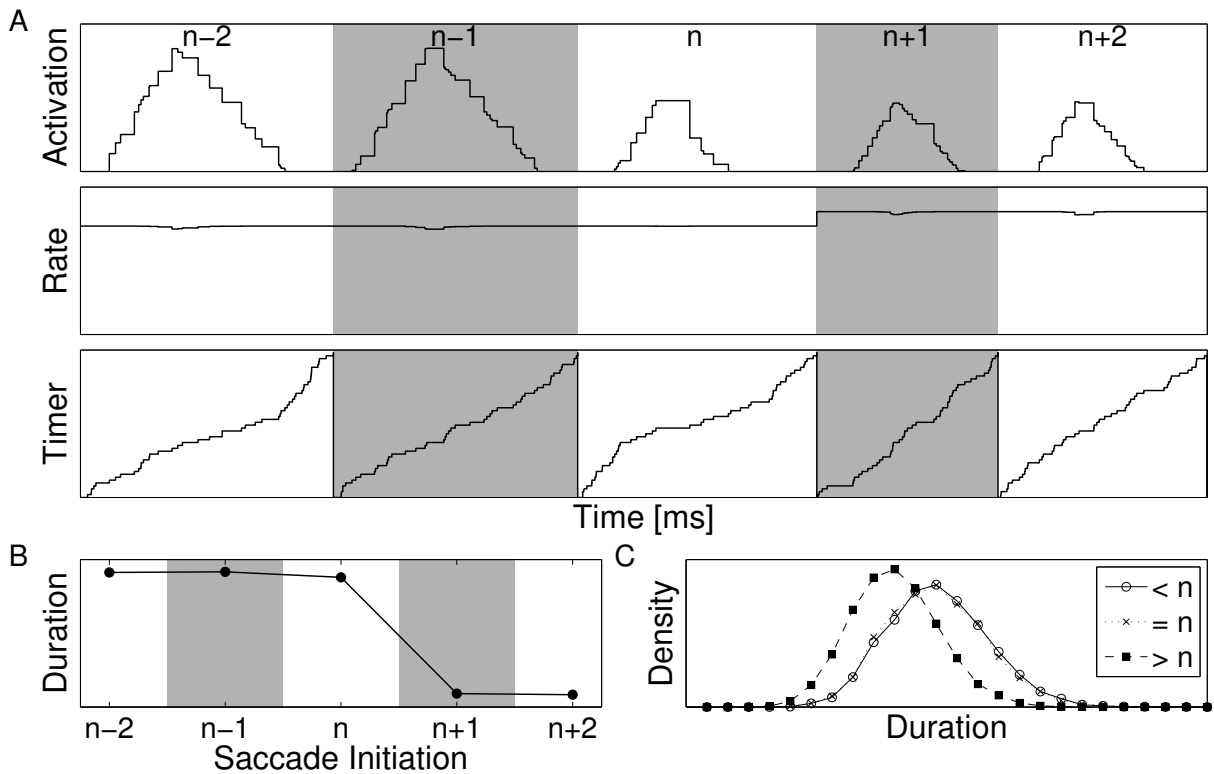


Figure 4.4: Illustration of saccade timer model: Processing demands decrease during the n th saccade initiation. Levels of the model: Foveal analysis (top panel), rate modulations (central panel), and the realized random walk (bottom panel). b) Mean saccade initiation intervals before ($< n$), during (n), and after adjustment ($> n$). c) Distribution of saccade initiation intervals before ($< n$), during (n), and after adjustment ($> n$).

4.2.4.2 Decreasing processing demands

In the next example, we examine saccade timing in the opposite case of decreasing processing difficulty (Fig. 4.4). The time courses of foveal analysis, rate modulation, and corresponding random walks are shown in Figure 4.4a. Activations resulting from foveal analysis reflect high processing demands during the first two saccade initiations and decrease during the n th saccade initiation. Since saccade timing is adjusted to high processing demands, almost no rate modulation is observed during the first two saccade initiations. A further decrease of processing demands during the n th saccade initiation does not affect rate. Hence, the observed rate remains almost constant during the first three saccade initiations. At the beginning of saccade initiation $n + 1$, saccade timing is adjusted to lowered processing demands and the rate of the random walk increases.

Mean saccade initiation intervals evolve correspondingly (Figure 4.4b). Durations are longest when saccade timing is adjusted to high processing demands. When processing demands decrease, mean saccade initiation interval is not immediately reduced. Only after a delayed adjustment of saccade timing at the beginning of saccade initiation $n + 1$, durations decrease significantly. Distributions of saccade initiation intervals are identical for high and low processing demands, when saccade timing is adjusted to high processing demands (Fig. 4.4c). After adjusting saccade timing to lower processing demands, the distribution shifts toward shorter saccade initiation intervals.

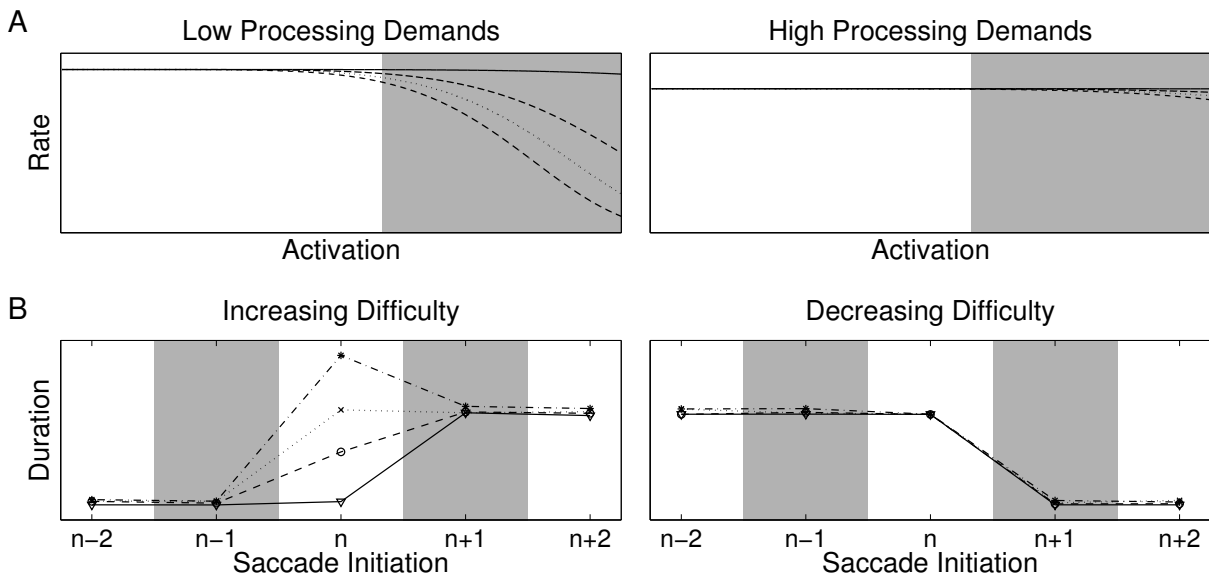


Figure 4.5: Foveal inhibition: Increasing processing difficulty. Rate modulations and mean saccade initiation intervals of four parameter combinations. a) Rate modulations when saccade timing is adjusted to low processing demands (left panel) and high processing demands (right panel). Low processing difficulties produce activations within the white area. High processing difficulties cause activations across the entire range (white and gray area). b) Mean durations over five successive saccade initiations when processing demands increase (left panel) and decrease (right panel). Four different forms of foveal inhibition are observed when processing demands increase during the n th saccade initiation: Delayed adjustment (solid line), partial adjustment (dashed line), perfect adjustment (dotted line), and overcompensation (dash-dotted line).

4.2.4.3 Local control: Modulations by foveal inhibition

Since foveal inhibition depends both on the time course of activations and on the set of parameters, a broad range of behaviors can be observed when processing demands change. The relationship between foveal inhibition and average saccade initiation intervals is illustrated for four parameter combinations in Figure 4.5. The left panel of Figure 4.5a displays rate modulations generated by foveal inhibition when saccade timing is adjusted to low processing demands. The equivalent curves for saccade timing adapted to high processing demands are shown in the right panel. For low activations, rates are higher when saccade timing is adapted to low processing demands (left panel) compared to when saccade timing is adapted to high processing demands (right panel). Thus, elementary steps will on average be shorter, when saccade timing is adapted to low processing demands.

In both panels of Figure 4.5, activations within the white area correspond to activations evolving from low processing demands, while activations in the gray area emerge when processing is highly demanding. Obviously, when activations are below the threshold for which they are adapted, rates are almost constant and barely differ between parameter combinations (left panel: white area; right panel: total area). However, strong rate modulations are observed, when activations exceed the threshold (left panel: gray area). The exact characteristics depend on the parameters chosen and range from an almost unaffected rate (solid line) to strong modulations (dash-dotted line). When saccade timing is adapted to high processing demands, neither low nor high activations induce

modulations of the random walk's rate. Nonetheless, some parameter combinations are more sensitive to increasing activations and show faint modulations for very high activations.

For each parameter combination, average durations of five successive saccade initiations are displayed in Figure 4.5b. Mean saccade initiation intervals are based on 10,000 simulations and the time course of activations used in the simulations corresponds to the time course of activations in the single run simulations (Figs. 4.3, 4.4). Across different parameter combinations, average saccade initiation intervals are similar before a change ($\leq n - 1$) and after adjusting the saccade timer to new processing demands ($\geq n + 1$). When processing demands increase (left panel), durations increase according to the strength of foveal inhibition during the n th saccade initiation interval. The increase can be compared to later well-adjusted saccade initiation intervals ($\geq n + 1$). When foveal inhibition is absent (solid line), mean saccade initiation intervals remain unaffected and a delayed adjustment of saccade initiation intervals is observed. With increasing foveal inhibition, saccade initiation intervals increase. For some parameter settings, durations increase somewhat (dashed line). In addition, a perfect adjustment can be seen (dotted line) or the prolongation might even be stronger than expected by well-adjusted saccade timing (dash-dotted line). Even though mean saccade initiation intervals might resemble adjusted saccade timing for some parameter combinations, the rate of a random walk is differentially affected during the n th saccade initiation and later well-adjusted saccade timing. For decreasing processing demands, evolution of average saccade initiation intervals is identical for all parameter combinations. The duration of the n th saccade initiation interval remains long and decreases afterwards ($\geq n + 1$). Such an asymmetric control of fixation durations, i.e., an immediate increase and a delayed decrease has been reported during reading (Kennison & Clifton, 1995) and visual search (Hooge et al., 2007). The increase, however, varied between experiments. While Kennison and Clifton (1995) observed some sort of overcompensation, Hooge et al. (2007) reported a partial adjustment.

In the previous example, we demonstrated a range of qualitative behaviors on saccade initiation intervals for increasing processing demands, while the temporal evolution of saccade initiation intervals was identical for decreasing processing demands. Next, we present three parameter combinations that differentially affect saccade initiation intervals when processing demands decrease (Figure 4.6). The solid line resembles rate modulations of the previous examples. The rate is almost unaffected by activations below the threshold to which saccade timing is adjusted (Figure 4.6a, left panel: white area; right panel: entire area). Activations exceeding this threshold cause strong rate modulations (left panel: gray area). Saccade initiation intervals for this parameter combination increase immediately when processing demands increase and remain long during the n th saccade initiation when processing demands decrease (Figure 4.6b). The dashed line shows strong modulations for the entire range of activations. Rate modulations are almost identical for saccade timing adjusted to low and high processing demands. In both cases, rate is high when processing demands are minimal and decreases rapidly when activations increase. Rate modulations are insensitive to the height of activations and quickly reach an asymptote. Since the duration of heightened activations is longer for high processing demands, saccade initiation intervals immediately adapt to new processing demands

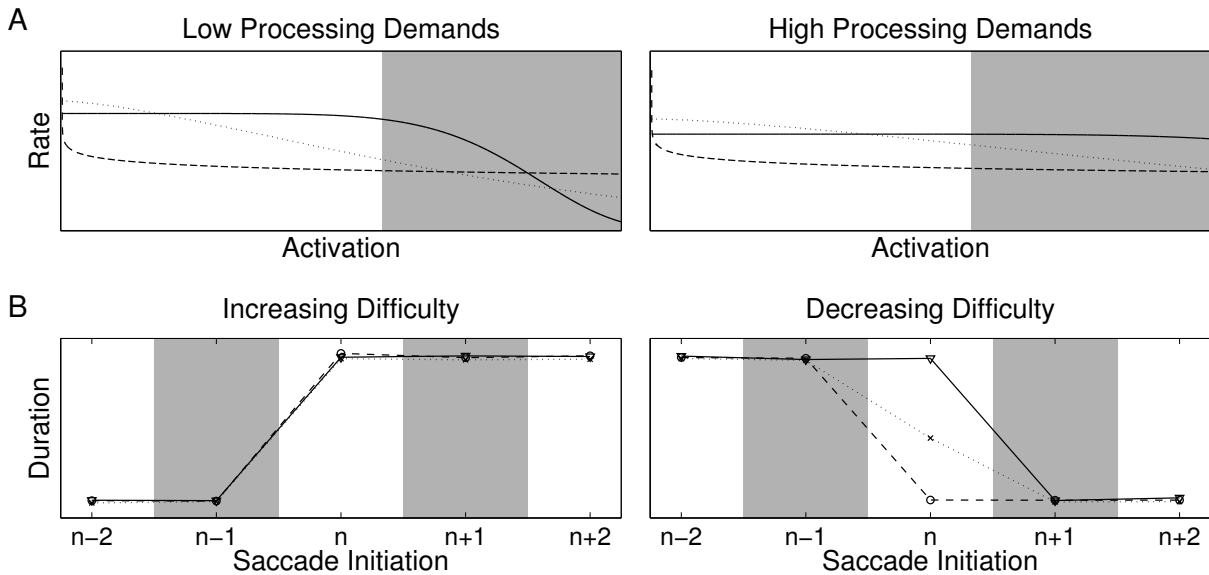


Figure 4.6: Foveal inhibition: Decreasing processing difficulty. Rate modulations and mean saccade initiation intervals of three parameter combinations. a) Rate modulations when saccade timing is adjusted to low processing demands (left panel) and high processing demands (right panel). Low processing difficulties produce activations within the white area. High processing difficulties cause activations across the entire range (white and gray area). b) Mean durations over five successive saccade initiations when processing demands increase (left panel) and decrease (right panel). Three different forms of foveal inhibition are observed when processing demands decrease during the n th saccade initiation: Delayed adjustment (solid line), partial adjustment (dotted line), and perfect adjustment (dashed line).

both when difficulty increases and decreases. Estimation of such parameters strongly support cognitive trigger theories. The third parameter combination (dotted line) shows rate modulations across the entire range of activations. The modulation, however, is stronger when processing is adjusted to low processing demands. For this parameter combination, average saccade initiation intervals shorten immediately when processing demands decrease. Compared to well adjusted saccade initiation intervals, the reduction is only partial.

4.2.4.4 Global control: Temporal adjustment of random timing and foveal inhibition

In the preceding examples, we focused on local effects of foveal inhibition for various parameter combinations. However, an important concept in our model is the continuous adjustment of saccade timing, which has only been assumed implicitly in previous indirect control theories. In our model adjustments occur on two levels. First, saccades are initiated autonomously, but the average duration T_j of this random time interval increases with increasing processing demands (Eq. 4.7). Second, strength of foveal inhibition scales with expected processing demands A_j (Eq. 4.6). Here, we illustrate the role of both processes by comparing simulations without adaptation, with one or two adaptive processes. Since fixation durations across tasks can be described by asymmetric control, we use the same parameters as in Figure 4.5 (perfect adjustment). With two adaptive processes, rate modulations behave as illustrated earlier (solid line, Fig. 4.7a). When saccade timing is adapted to low processing demands (left panel), rate of the random walk is only modulated by activations above the adjusted level (gray area).

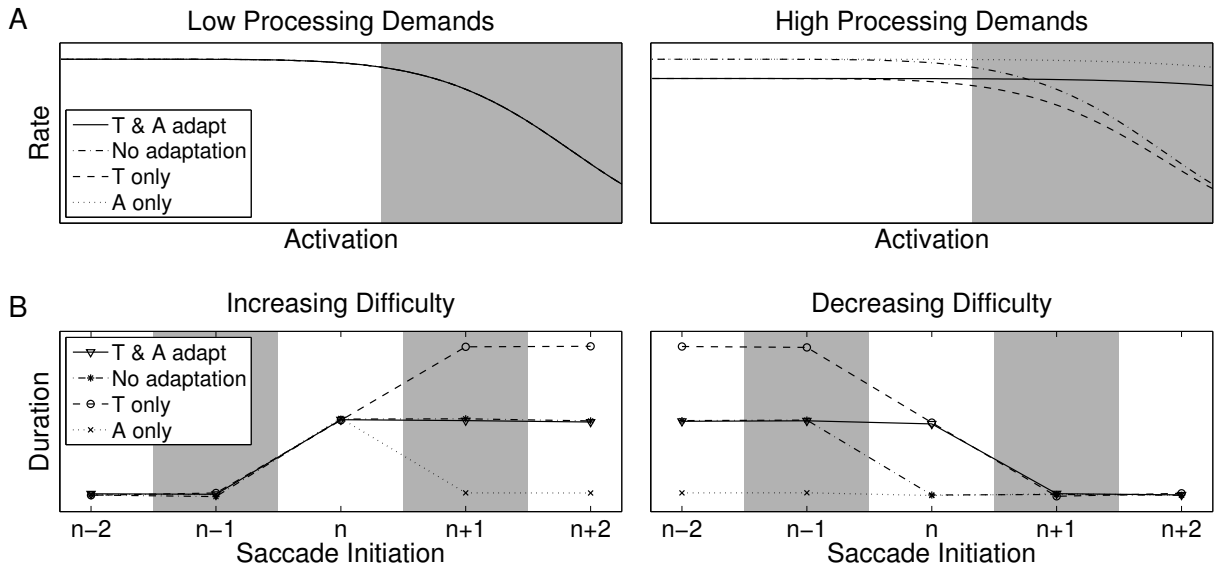


Figure 4.7: Saccade timer adjustments. Role of adjusting the average saccade timer interval T_j and the expected processing difficulty A_j . a) Rate modulations when saccade timing is adjusted to low processing demands (left panel; white area) and high processing demands (right panel; entire area). b) Mean durations over five successive saccade initiations when processing demands increase (left panel) and decrease (right panel).

When saccade timing is adapted to high processing demands (right panel), overall rate is reduced and remains unmodulated by high activations. Corresponding saccade initiation intervals show an asymmetric control pattern with immediate prolongations and delayed reductions, when processing demands change (Fig. 4.7b).

Without adaptation (dash-dotted line, Fig. 4.7), rate modulations are independent of previous processing demands, which leads to identical curves in the left and right panel. Since high activations always cause rate modulations in the model, the influence of foveal inhibition is symmetric and fixation durations immediately increase and decrease, when processing demands change. Hence, saccade timing without adaptation resembles control by cognitive triggers.

In the next simulation, the mean timer interval T_j adapts without simultaneous adaptation of foveal inhibition (dashed line, Fig. 4.7). Rates of the random walk are generally reduced, when saccade timing is adapted to high processing demands (right panel), and rate modulations are strong both when adapted to low and high processing demands. As a consequence, average saccade initiation intervals are symmetrically modulated in two steps. In a first step, foveal inhibition immediately prolongs and reduces saccade initiation intervals (saccade initiation n). In a second step, saccade initiation intervals are further modulated since the autonomous timer adapts with a temporal delay (saccade initiation $n + 1$).

Finally, if the scaling factor of foveal inhibition A_j adapts without adaptation of the timer (dotted line), rate modulations are only observed, when processing is adjusted to low processing demands. As a consequence, only a single fixation is prolonged, when processing demands increase, and no fixation, when processing demands decrease. As revealed by our simulations, adjustments of the mean saccade timer interval T_j lead to delayed and sustained changes in saccade initiation intervals, while adjustments of the

scaling factor A_j determine the local prolongation of single saccade initiation intervals. Asymmetric control of saccade initiation is only generated, when both processes adapt simultaneously over time.

4.2.5 Immediacy & lag effects

The majority of eye-movement studies focused on average durations of first fixations, single fixations, and gaze durations (Rayner, 2009). As demonstrated above, our model is able to generate differences in mean fixation durations via foveal inhibition and, thus, is generally in agreement with immediate effects of the current fixation location on corresponding durations. Simulations of immediacy effects in reading can be found in the Supplementary Information. Lag effects, where processing difficulty of the fixated object spills over to the next fixation, have also been observed (Rayner & Duffy, 1986). During reading, fixations on word $n + 1$ are longer when the preceding word n is a low-frequency word compared to a high-frequency word (Henderson & Ferreira, 1990; Kennison & Clifton, 1995; Schroyens, Vitu, Brysbaert, & d'Ydewalle, 1999). Interestingly, the lag-frequency effect, i.e., the modulation of the fixation duration on word $n + 1$, is sometimes even larger than the immediacy effect on word n (Kliegl et al., 2006; Schad, Nuthmann, & Engbert, 2010). Lag effects in ICAT may be generated by two mechanisms. First, if processing has advanced sufficiently, the saccade timer is adjusted to previous processing demands, which in turn affects subsequent fixation durations. Second, if processing is slower, foveal inhibition may have a delayed impact on the next fixation. Depending on the exact time course of processing, either the current fixation, the next fixation, or even both may be prolonged. Hence, our model generates effects on subsequent fixations, as observed in gaze durations, and accounts for shifts of effects from first-fixation durations to later fixations, for example, when preview of a item is prevented (Inhoff & Rayner, 1986; Reingold et al., 2012; Sereno & Rayner, 2000). In general, mean fixation durations of one or more successive fixations may be replicated by the ICAT model.

4.2.6 Labile saccade programming

Until now, we focused on the duration between the initiation of two adjacent saccade programs, while neglecting the role of saccade programming and execution. In ICAT a random timer is constantly active and saccade programs are initiated whenever a certain threshold is reached. Saccade programs consist of two stages, a labile stage, which can be subject to cancelation, and a non-labile stage, which is resistant to further changes. The labile stage has a mean duration τ_l and is canceled if a second saccade program is initiated during this stage. The canceled saccade program is replaced by a new labile saccade program, which in turn may be canceled by another new saccade program. Only after transition from the labile stage to the non-labile stage a saccade is imminent and the current fixation is terminated.

The main motivation for two stages of saccade programming derives from the double-step paradigm in saccade generation (Becker & Jürgens, 1979), which revealed that saccades to a first saccade target can be canceled by the appearance of a second saccade target up to 250 ms after presentation of the first. Later presentations led to a sequence of

fixations on both targets. In our model, this is captured by a “point-of-no-return” at the transition from a labile to a non-labile stage. The assumption of two stages of saccade programming in models of eye-movement control during reading was introduced by Reichle et al. (1998) and has been applied to other models of eye-movement control during reading (Engbert & Kliegl, 2001; Engbert et al., 2002) and scene perception (Nuthmann et al., 2010).

In an earlier section, we presented the concept of a random walk to generate intervals between two saccade initiations. Here, we take advantage of the stochastic simulation of Markov processes (Gillespie, 1978) to implement a coherent framework of stochasticity at multiple levels. Each component of saccade control, i.e., saccade initiation, labile and non-labile saccade programs, and saccade execution can be described by separate random-walk processes. In order to get a better estimate of fixation durations, we added a random walk for the labile saccade programming stage that can be canceled by the initiation of a new saccade program. Durations of non-labile saccade programs and durations to execute saccades depend on factors like saccade amplitude and were excluded at this level.

The dynamical state of the ICAT model is defined by a vector $S_m = (m_1, m_2)$ representing the states of two random walks, i.e., $m_1 = 0, 1, 2, \dots, N_t$ for saccade timing and $m_2 = 0, 1, 2, \dots, N_o$ for the labile saccade program. Two transitions are possible from each state $S_m = (m_1, m_2)$ to state $S_n = (m_1 + 1, m_2)$ or $(m_1, m_2 + 1)$. Thus, while multiple processes may be active simultaneously, each transition affects only one random walk.

Mathematically, we have to compute the transition probability of the model from state S_m at time t , having arrived there at time $t - \tau$, to an adjoined state S_n . Following Gillespie (1978), we can compute a realization of the time step dt from the total transition probability W_m . The time step is drawn from an exponential waiting time distribution (see Eq. 4.1), i.e.,

$$\rho(\tau) = W_n \exp \{-W_n \tau\} \quad \text{with} \quad W_n = \sum_{n \neq m} W_{nm}, \quad (4.8)$$

where W_n is the sum of all transition rates W_{nm} from the current state S_m to an adjoined state S_n . Since saccade initiation and labile saccade programming are two independent one-step processes, the total transition probability $W_n(t)$ at time t is given by

$$W_n(t) = w_j(t) + w_{lab}(t) \quad (4.9)$$

where $w_j(t)$ is the time-dependent transition probability of the random walk implemented in the ICAT model of saccade timing (see Eq. 4.4) and w_{lab} corresponds to the transition probability of the labile saccade program.

While the transition rate $w_j(t)$ of the saccade timer is always non-zero, the random walk of the labile stage is only active after saccade initiation. When the random walk of the saccade timer reaches a threshold, the labile program starts, $w_{lab}(t) > 0$, and terminates when reaching the oculomotor threshold, $w_{lab}(t) = 0$. After initiating a labile saccade program, the rate of the random walk is given by

$$w_{lab}(t) = \frac{N_o}{\tau_{lab}} \quad \text{during labile stage}, \quad (4.10)$$

where N_o is the number of states of oculomotor random walks, τ_{lab} denotes the average duration of the labile stage. If the labile stage is canceled by a new saccade program, the state of this random walk begins anew, i.e., $m_2 = 0$.

After computation of the time step dt , a transition has to be selected. Probabilities of possible transitions are given by relative transition probabilities (Gillespie, 1978), i.e.,

$$p_n(t) = \frac{W_{nm}(t)}{W_n(t)}. \quad (4.11)$$

In summary, the algorithm proposed by Gillespie (1978) allows to simultaneously simulate multiple independent random walks. The computation is performed in three iterative steps. First, a total transition probability $W_n(t)$ is computed by summing the rates of all random walks. Second, the time until the next transition dt is determined by drawing a pseudo-random number from an exponential distribution (Eq. 4.8). Since the exponential distribution and corresponding random number depends on the total transition probability, time steps dt decrease with increasing number of active random walks. Third, only one random walk moves during each transition. Probability of a step is given by relative transition probabilities $p_n(t)$ of each random walk (Eq. 4.10). After a transition the process starts anew. When a random walk reaches a threshold, random walks are reset and may even be stopped. The procedure ensures that distributions of durations for each class of random walks are independent and correspond to the rates used during the simulation.

A histogram of 1,000,000 simulated fixation durations is shown in Figure 4.8 (bold line). As in regular fixation durations, the distribution has a pronounced peak and is skewed to the right. The rightward skew is generated by fixation durations that have been prolonged by one or more cancelations (thin lines). While fixation durations with no cancelations of the labile stage are shortest and have the smallest variance (solid line, $N = 913,953$), average fixation duration and variance increases with increasing number of cancelations. Overall, 9% of fixation durations were affected by cancelations. As can be seen from the plot long fixation durations are primarily generated by saccade cancelations. In agreement with this, simulations in the Supplementary Information were also run without a cancelation mechanism. While simulations captured effects in mean fixation durations, long fixation durations were generally underestimated. Cancelations of existing saccade programs seem to be an important factor for the variability in fixation durations.

4.3 A model of eye guidance during scanning

After introducing the general principles of fixation duration control of the ICAT model, we now discuss how the model may be combined with assumptions about spatial control. While it is possible to use ICAT's saccade timing within a serial attention shift model of spatial control of eye movements, we argued earlier (Engbert & Kliegl, 2011) that indirect control principles of fixation durations are more naturally combined with a dynamic field theory (Amari, 1977; Erlhagen & Schöner, 2002). As an example for a dynamic

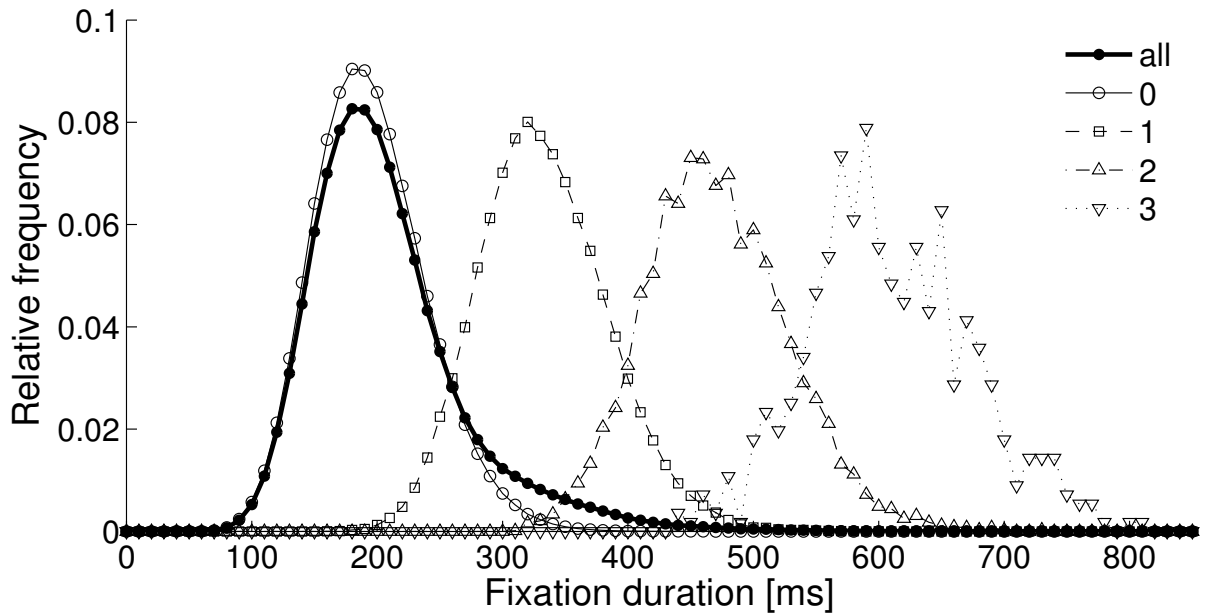


Figure 4.8: Histograms of saccade initiation times with a binwidth of 10 ms (all, $N = 1,000,000$), saccade initiations without cancellation of the labile saccade program (0, $N = 913,953$), with one cancellation (1, $N = 78,658$), two cancellations (2, $N = 6,785$), three cancellations (3, $N = 558$). Four and five successive cancellations occurred rarely and were observed 45 times and once, respectively. Distributions were normalized relative to the included number of fixations.

field theory for eye-movement control in reading, we proposed the SWIFT model for the generation of saccades during reading (Engbert et al., 2005).

4.3.1 Dynamic field of activations

In SWIFT, a single set of activations $\{a_n(t)\}$ is used to keep track of lexical processing of word $n = 1, 2, 3, \dots, N$ and for target selection. As a result, all types of saccades observed in reading experiments are predicted by the set of distributed activations. In the following, we assume that a discrete set of items is available, so that a unique mapping between items and activations exists. For the numerical simulations we use a scanning task with a horizontal row of stimuli. This simplification is not a fundamental limitation of the modeling approach (the dynamic field theory of movement planning is continuous in both time and space). For more complex visual search tasks or scene viewing, the set of activations can be extended to a continuous two-dimensional field.

The set of activations $\{a_n(t)\}$ is shaped by processing and can be interpreted as a (dynamical) saliency map (Koch & Ullman, 1985) which is used for the selection of saccade targets. Temporal evolution of each activation $a_n(t)$ is divided into two stages. During a first stage, activation $a_n(t)$ increases and, consequently, the probability of selecting object n as the next saccade target increases (i.e., it becomes more and more salient). After reaching a maximum value, A_j , activations decrease, until they return to a minimum of $a_n(t) = 0$. Here we consider the case that a stimulus or object n is completely processed when the minimum activation is reached. However, in tasks with recurrent visits of a particular region (e.g., scene viewing), a natural extension of our model would be to permit multiple processing cycles after a first fixation within the region of object n .

4.3.2 Processing rate and visual acuity

Activation-field dynamics are based on distributed processing (Engbert et al., 2002; Engbert & Kliegl, 2011). As one of the landmark findings in the 1970s, the perceptual span has been explored in detail in reading (McConkie & Rayner, 1975; Rayner, 1975; Rayner & Bertera, 1979). Here we use the operational definition of *processing span* as the area around the fixation location from which information is extracted for the control of eye movements. At least two factors contribute to the shape of the processing span: Visual acuity and task-dependent attention allocation. It is important to note that for particular aspects of information extraction, different (and more rigorously defined) notions of processing spans are proposed, however, the model developed here aims at a very general concept of processing, not addressing the details of particular tasks.

Visual acuity is a function of the distance from the center of the visual field. The horizontal distance (or eccentricity) ε_n of a stimulus n to the fixation position is given by

$$\varepsilon_n(t) = \chi_n - k(t), \quad (4.12)$$

where χ_n represents the center of stimulus element n and $k(t)$ the absolute fixation position⁵ at time t .

In addition, the perceptual span is asymmetrical during reading (McConkie & Rayner, 1976; Pollatsek et al., 1981) and is expected to be asymmetrical in left-to-right scanning tasks as well. Following Engbert et al. (2005), we approximate the spatial properties of the processing span by an asymmetric Gaussian function to capture the relation between processing rate and visual eccentricity. The maximum processing rate is found at the center of fixations and decreases monotonically with increasing eccentricity. Due to the asymmetric span, processing rate declines steeper to the left than to the right. Mathematically, processing rate $\lambda_n(t)$ of stimulus element n at time t is computed by

$$\lambda_n(t) = \lambda_0 \exp\left(-\frac{\varepsilon_n^2(t)}{2\sigma^2}\right) \text{ with } \begin{cases} \sigma = \sigma_L, & \text{if } \varepsilon_n(t) < 0 \\ \sigma = \sigma_R, & \text{if } \varepsilon_n(t) \geq 0 \end{cases} \quad (4.13)$$

where the width of the processing span is characterized by σ_L (extension to the left) and σ_R (extension to the right). The parameter λ_0 is a normalization constant, so that processing rate over the total span sums to one. Hence, λ_0 is a function of σ_L and σ_R ,

$$\lambda_0 = \sqrt{\frac{2}{\pi}} \frac{1}{\sigma_L + \sigma_R}, \quad (4.14)$$

and is not a free parameter in our model.

4.3.3 Temporal evolution of activations

Before preprocessing a stimulus is unknown, after processing the object is identified. In both cases activations will have a value of zero and will not attract the eyes as

⁵In a two-dimensional version, the scalar quantities $k(t)$, χ_n , and $\varepsilon_n(t)$ would be vector-valued variables $\vec{k}(t)$, $\vec{\chi}_n$, and $\vec{\varepsilon}_n(t)$, respectively.

possible saccade targets. As noted above, the uni-modal relation between activation and processing can be relaxed to multiple processing cycles for specific tasks. Following Engbert et al. (2002, 2005), the temporal evolution of activations is controlled by a system of N coupled ordinary differential equations,

$$\frac{da_n(t)}{dt} = f_n(t)\lambda_n(t) - \kappa, \quad (4.15)$$

where (i) $f_n(t)$ is a factor representing the two processing stages with increasing and decreasing activation, (ii) $\lambda_n(t)$ is the processing rate of stimulus element n , and (iii) κ gives the strength of a global decay process. The decay process induces a slow (compared to processing speed in foveal vision) decrease at a constant rate across the entire activation field and is motivated by memory leakage. During preprocessing, $f_n(t) = f$, activation $a_n(t)$ of symbol n rises to its maximum value A_n , which is interpreted as the processing difficulty. In a second processing stage, $f_n(t) = -1$, activation $a_n(t)$ declines to zero.

4.3.4 Target selection

In our model, processing over time is reflected in a set of activations $\{a_n(t)\}$. One of the major advantages of this field-theoretic approach (Erlhagen & Schöner, 2002; Engbert et al., 2002) is that relative activations determine target-selection probabilities. Except for specification of some details for the computation of probabilities from the set $\{a_n(t)\}$ at time t , no additional assumptions are necessary. Here we implement target selection, by considering all stimulus elements n with some non-vanishing activation, $a_n(t) > 0$. Mathematically the probability $\pi_n(t)$ of selecting a stimulus element n as a saccade target at time t is given by its relative activation,

$$\pi_n(t) = \frac{a_n^\gamma(t)}{\sum_{j=1}^N a_j^\gamma(t)} \quad \text{with} \quad \sum_{n=1}^N \pi_n(t) = 1, \quad (4.16)$$

where N is the number of target objects and the exponent γ is a measure of stochasticity in the target selection process. Two extreme forms of target selection can be distinguished. For $\gamma \rightarrow \infty$ target selection is a deterministic process, where the highest activation is chosen as the next saccade target (“winner-takes-all”). In contrast, for $\gamma = 0$ all activated symbols have the same probability to be chosen as the target during the next saccade (random target selection). In our simulations, this parameter is set to a value of $\gamma = 0.1$ (see also Engbert & Kliegl, 2011).

4.3.5 Saccade programming

As mentioned earlier, preparation of saccades is a two-stage process with a labile and a non-labile programming stage (Becker & Jürgens, 1979). After initiation of a new saccade program in the ICAT model, a labile stage with mean duration τ_l starts. If a second saccade program is initiated during this stage, the labile saccade program will be canceled and replaced by a new labile saccade program. After termination of the labile stage, a non-labile stage with average duration τ_{nlab} is entered. If a new labile

Table 4.1: Transition events and transition rate.

| Random walk | Transition from $S_m = (m_1, m_2, m_3, m_4)$ to $S_n = \dots$ | | | | Transition rate |
|---------------------------------|---|-----------|----------|----------|--------------------|
| Saccade timer ^a | $m_1 + 1$ | m_2 | nl | ex | $\omega_j(t)$ |
| Labile program ^a | m_1 | $m_2 + 1$ | nl | ex | $\omega_{lab}(t)$ |
| Non-labile program ^a | m_1 | m_2 | $nl + 1$ | ex | $\omega_{nlab}(t)$ |
| Saccade execution ^a | m_1 | m_2 | nl | $ex + 1$ | $\omega_{ex}(t)$ |

^aAfter exceeding a threshold random walks are reset to zero.

saccade program is initiated while the non-labile stage is active, two saccade programs will be programmed in parallel resulting in reduced fixation durations during the next fixation (McPeck et al., 2000).⁶ Saccade targets after short saccade latencies are based on information accumulated during the previous fixation (Caspi, Beutter, & Eckstein, 2004) and both coding and maintenance of a second saccade target before initiation of the first saccade has been reported for neurons in the superior colliculus (McPeck & Keller, 2002). The transition from a labile to non-labile programming stage triggers the selection of the next saccade target (see Eq. 4.16). After termination of a non-labile saccade program, a saccade is executed with mean duration τ_{ex} . Since *saccadic suppression* strongly reduces visual input during saccades (Matin, 1974), preprocessing is interrupted immediately after the execution of a saccade for 50 ms. The temporal delay of this interruption is in accordance with the eye-brain lag (Fuxe & Simpson, 2002; Lamme & Roelfsema, 2000). In the second processing stage, symbol identification is unaffected by saccadic suppression, since visual input is more critical for early processing.

4.3.6 Stochastic simulation of saccade programming and execution

In the section on saccade timing, we introduced stochastic simulation of multiple random walks within a coherent framework (Gillespie, 1978). Here, we extend this framework to four Markov processes in order to implement all levels of saccade control, i.e., saccade initiation, labile and non-labile saccade programs, and saccade execution. In this case, the dynamical state of the model is defined by a vector $S_m = (m_1, m_2, m_3, m_4)$, where $m_1 = 0, 1, 2, \dots, N_t$ is the state of saccade timing, m_2 is related to the labile saccade program, m_3 represents the non-labile program, and m_4 denotes the state of saccade execution. Accordingly, there are four possible transitions from state S_m to the adjoined states S_n (Table 4.1).

Since saccade timing, saccade programming, and saccade execution consist of four independent one-step processes, total transition probability $W_n(t)$ at time t is given by (cf., Eq. 4.8),

$$W_n(t) = w_j(t) + w_{lab}(t) + w_{nlab}(t) + w_{ex}(t) \quad (4.17)$$

where $w_j(t)$ is the time-dependent transition probability of the random walk implemented in the ICAT model of saccade timing (cf., Eq. 4.4) and the transition probabilities w_{lab} , w_{nlab} , and w_{ex} correspond to the transition probabilities of the labile/non-labile

⁶Percent of concurrent saccade programs was estimated by numerical simulations for Experiment 1 (10.5%) and Experiment 2 (2.5%). The huge difference between both simulations results from the differences in saccade timing. Parallel programming of saccades is much more likely if saccades are initiated after short time intervals.

saccade programs and saccade execution. Calculation of the waiting time dt as well as the corresponding transition probabilities $p_n(t)$ can be done by using Equations (4.1) and (4.11).

While the transition rate $w_j(t)$ of the saccade timer is always non-zero, random walks of the oculomotor system are only active, when the corresponding saccadic process has been initiated. For example, the labile program starts when the random walk of the saccade timer reaches the threshold and terminates when reaching its own threshold while simultaneously triggering the non-labile stage. After entering a stage of saccade programming or during the execution of a saccade, rates of corresponding random walks are given by

$$\begin{aligned}
 w_{lab}(t) &= \frac{N_o}{\tau_{lab}} h_j[a_f(t)] && \text{during labile stage} \\
 w_{nlab}(t) &= \frac{N_o}{\tau_{nlab}} && \text{during non-labile stage} \\
 w_{ex}(t) &= \frac{N_o}{\tau_{ex}} && \text{during saccade execution}
 \end{aligned} \tag{4.18}$$

where N_o is the number of states of oculomotor random walks, τ_{lab} , τ_{nlab} , and τ_{ex} denote the average duration of the respective process, and $h_j[a_f(t)]$ is the strength of foveal inhibition (see Eq. 4.4). Since foveal inhibition ranges between 0 to 1, transition rates of labile saccade programs may be reduced by foveal inhibition.

The interplay of all random walks during a trial is illustrated in Figure 4.9a. Figure 4.9b is an enlarged view of the gray part of Figure 4.9a. The random walk of the autonomous saccade timer is shown at the bottom. Random walks of the labile and non-labile saccade programming stages are shown in the central rows, and the random walk of the executed saccade is plotted at the top. The random walk of the saccade timer is continuously active and rises towards the predefined threshold N_t . When reaching this threshold a cascade of events begins. First, the random walk is reset to zero; second, a labile saccade program is initiated. Now, two random walks evolve simultaneously over time with different mean durations and thresholds (active random walks are plotted with black lines). At the end of the labile saccade program, the corresponding random walk is inactivated and set to zero and the target of the next saccade is chosen. At the same time, the random walk of the non-labile program starts. Likewise, this random walk is reset and inactivated at the end of the non-labile saccade program and triggers the random walk of the executed saccade. After saccade execution, all but the random walk of the saccade timer are inactive until it reaches the threshold anew.

A timeline of events is shown in Figure 4.9c. The upper column shows the sequence of saccade programs. Until a labile saccade program is initiated, the saccadic system remains in a decision mode (D) where only the saccade timer is active. Subsequently a labile (L) and non-labile saccade program (N) is executed, followed by the executed saccade (S). Fixations (F) comprise the time between two saccades which consist of three different parts: A decision period, the duration of a labile saccade program, and the duration of a non-labile saccade program. Variability of fixation durations is generated at two independent levels: Saccade initiation and saccade programming. Variability on

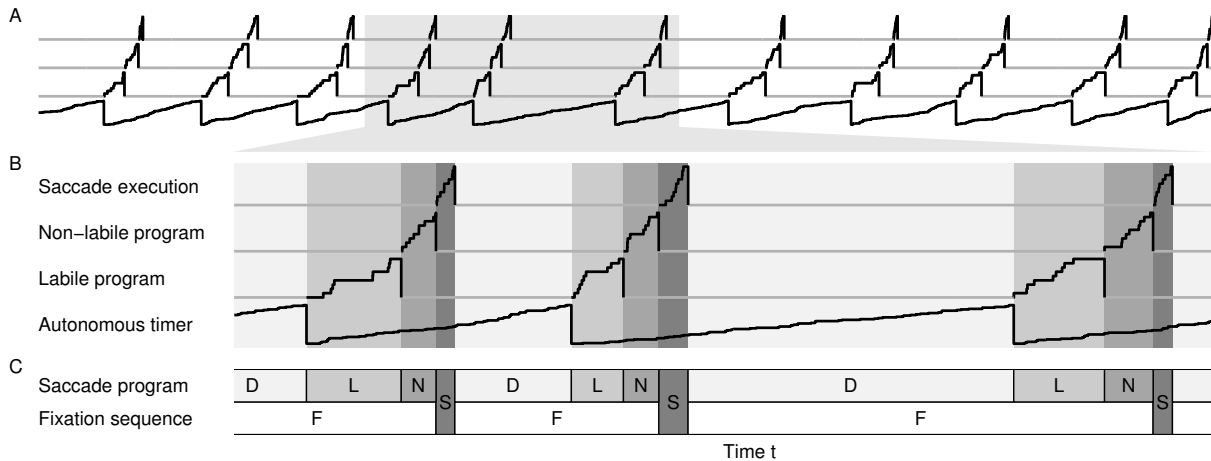


Figure 4.9: Parallel simulation of random walks for sub-processes. (a) Simulation of a single trial. (b) Magnification of highlighted area. In the model random walks determine stochasticity at four different levels: The timer initiating new saccade programs, labile and non-labile saccade programs, as well as the executed saccades. Periods with active random walks, i.e., $\omega > 0$, are plotted as black lines; inactive random walks, i.e., $\omega = 0$, are plotted as gray lines. (c) Sequence of events at the saccadic level (saccade program) and observable behavioral level (fixation sequence). Fixations (F) are the time between two saccades (S) and consist of a decision period (D), a labile saccade program (L), and a non-labile saccade program (N).

the level of saccade initiation affects the decision period, while variability on the level of saccade programming affects durations of the labile and non-labile stages.

According to the stochastic simulation framework, multiple random walks can be active simultaneously. Constraints imposed by values of the estimated parameters and by the architecture of the model, however, hamper the execution of multiple random walks. For our subsequent simulations we estimated the percentage of time with a single active random walk (Experiment 1 $\approx 15.75\%$; Experiment 2 $\approx 35.72\%$), two random walks active in parallel (82.26%; 64.00%), and three or more active processes (1.99%; 0.27%).

4.3.6.1 Oculomotor errors in saccade generation

Assumptions about saccadic errors in SWIFT (Engbert et al., 2005) are based on results by McConkie et al. (1988). During reading, saccades are directed toward the center of a word, but are modulated by a systematic and a random error component, so that the observed mean fixation position is typically characterized by a small deviation from the word center. Both error components can be observed in simple oculomotor tasks (Kapoula, 1985) as well as visual search tasks (Trukenbrod & Engbert, 2007). Across tasks both components contribute differently to the observed saccade amplitudes. Recent results demonstrated that such stochastic variation of landing position can be explained by Bayesian estimation in the case of text reading (Engbert & Krügel, 2010), which might offer a more parsimonious implementation of oculomotor errors for future modeling work.

The realized saccade length l consists of three linearly combined components (McConkie et al., 1988), i.e.,

$$l = l_I + l_{SRE} + l_G. \quad (4.19)$$

The intended saccade amplitude l_I is the distance to the *optimal viewing position* of the next target (McConkie et al., 1989), which is modified by a systematic error component l_{SRE} and by random noise l_G in the oculomotor system. In our simulations the intended saccade amplitude is the distance of the fixation position to the center of the next saccade target.

The systematic error component is known as *range error* (Kapoula, 1985; Poulton, 1981), which produces a systematic deviation from the intended saccade amplitude l_I towards a preferred saccade length l_0 . The deviation is proportional to the difference between intended and preferred saccade length,

$$l_{sre} = \delta_{SRE} (l_0 - |l_I|), \quad (4.20)$$

with a factor δ_{SRE} regulating the strength of the saccadic range error. Because of this systematic error component, saccades tend to overshoot the target when the target is closer to the launch site than the preferred saccade length, $l_0 > l_I$, and tend to undershoot the target when it is farther away, $l_0 < l_I$.

In addition, saccade amplitudes are altered by a random error component. The random error is implemented as Gaussian noise with zero mean and standard deviation σ_G . Variance of random errors increases with movement amplitude in almost all motor control processes (Poulton, 1981). For simplicity, we assume a linear relation between standard deviation σ_G and intended saccade amplitude l_I with an intercept δ_0 and slope δ_1 ,

$$\sigma_G = \delta_0 + \delta_1 |l_I|. \quad (4.21)$$

4.3.6.2 Mislocated fixations

A substantial proportion of variability in fixation durations can be attributed to the fixation position relative to the center of an object. During reading, average fixation durations are longest near word centers and decrease towards word edges (Vitu et al., 2001). During visual search, fixation durations decrease with increasing distance to the stimulus element (Trukenbrod & Engbert, 2007). Nuthmann et al. (2005; see also Engbert & Nuthmann, 2008) suggested that the oculomotor system compares intended and realized saccades and immediately initiates a new saccade program when both differ. Such a comparison could be based on an efference copy and might be independent of new visual input. Thus, the initiation of a corrective saccade occurs immediately after the end of a saccade without temporal delay. Corrective saccades have been incorporated into models of eye-movement control during reading and account for fixation duration differences within words (Engbert et al., 2005; Reichle, Warren, & McConnell, 2009).

We calculated the horizontal distance $\Delta_k(t)$ of landing site $k(t)$ at the beginning of fixation n at time t to the center of the intended target stimulus χ_{tar} , i.e.,

$$\Delta_k(t) = |\chi_{tar} - k(t)|. \quad (4.22)$$

We assume that the oculomotor system is more likely to detect a mislocated fixation with increasing difference between realized and intended saccade. The probability $\eta_n(t)$ to immediately initiate a new saccade program at the beginning of fixation n at time

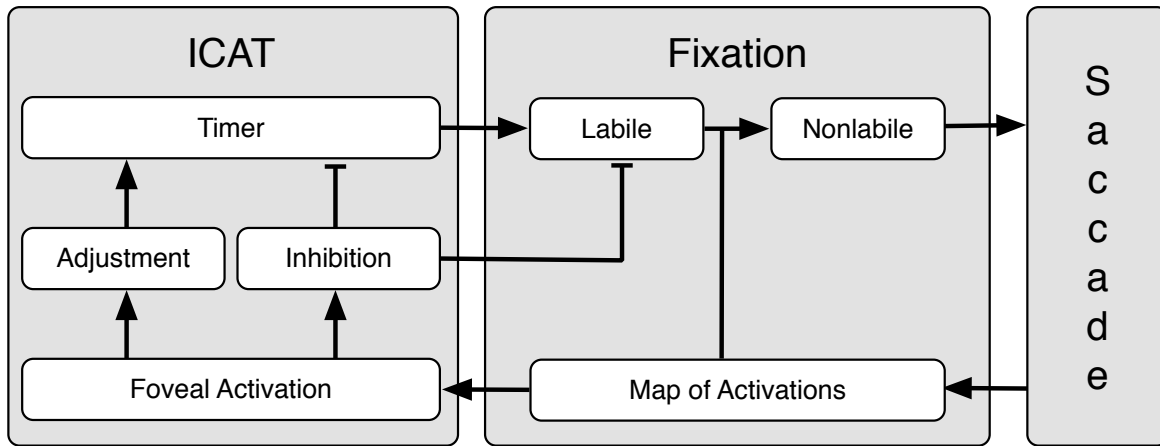


Figure 4.10: Model overview. The ICAT principles incorporated into a general model of eye-movement control.

t is a symmetric function around the center of the target stimulus and calculated by a sigmoidal function scaled to values between $0 \leq \eta_n(t) \leq 1$,

$$\eta_k(t) = \frac{\tanh(v_1 \Delta_k + v_2) + 1}{2}, \quad (4.23)$$

where v_1 and v_2 are two free parameters affecting the point of inflection and slope of the function.

4.3.7 Model overview

Figure 4.10 gives an overview of the full model architecture. Saccade initiation is controlled by the ICAT principles, illustrated in the leftmost part of the figure. Saccades are triggered by an autonomous saccade timer (principle Local I). After a random time interval a new saccade program is initiated, which consists of two stages. During the labile programming stage saccades may still be modified or even canceled. When passing into a non-labile programming stage, a saccade target is selected and saccade execution is inevitable. Saccade targets will be chosen from an activation field defined as a set of activations. Temporal dynamics in the activation field strongly depend on the current fixation position and change after each saccade correspondingly. As stated earlier, foveal processing feeds back to the ICAT model. Thus, foveal activations are used to inhibit the initiation of new saccades (principle Local II) and adjust saccade timing to new processing demands (principle Global).

4.4 Simulation studies

Using two variants of a simple scanning task (see Hooge & Erkelens, 1998, for a related task), we investigated the control of fixation durations in our model when equipped with a realistic oculomotor machinery. In the first experiment, participants searched for a ring in an array of Landolt-Cs. Fixation duration adjustments were investigated by

| | | | | | | | | |
|--------------------|----|----|----|---|---|---|---|---|
| a) Low Difficulty | ○ | ○ | ○ | ○ | ○ | ● | ● | ○ |
| b) High Difficulty | ○ | ○ | ○ | ○ | ● | ○ | ○ | ● |
| c) Increasing | ● | ○ | ○ | ● | ○ | ○ | ○ | ○ |
| d) Decreasing | ● | ○ | ● | ○ | ○ | ○ | ● | ○ |
| Relative position | -3 | -2 | -1 | 0 | 1 | 2 | 3 | 4 |

Figure 4.11: Sequence of fixated symbols. Processing demands change at relative position 1 in the two experimental conditions. a) Baseline condition with low difficulty: All stimulus elements have wide gaps. b) Baseline condition with high difficulty: All stimulus elements have narrow gaps. c) Experimental condition with increasing difficulty: At relative position 1 gap size decreases and remains narrow. d) Experimental condition with decreasing difficulty: At relative position 1 gap size increases and remains wide.

a stepwise change of processing demands during the trial. In the second experiment, the same set of stimuli was used in a gaze-contingent task to limit fixation duration adjustments to foveal processing. In both tasks we examined the model's performance on mean fixation durations as well as fixation duration distributions. In addition, we explored target selection, effects related to the fixation position relative to the fixated symbol, and fixation durations before different saccade types. All analyses reported here were limited to target absent trials.

4.4.1 Task

Participants were instructed to scan sequences of eleven symbols from the left to the right on a computer display and to search for a target stimulus (see Appendix 4.7 for details). We used a ring as target and Landolt-Cs as distractors. The sequence of symbols in each condition is displayed in Figure 4.11. We varied target-distractor similarity by gap size and expected higher fixation durations on symbols with small gaps due to higher processing difficulty. As baseline conditions we measured eye movements when the entire sequence was composed of distractors with large gaps (low difficulty) or small gaps (high difficulty). In the remaining conditions gap size changed at an intermediate position of the sequence. As a result, participant's performance had to adapt from distractor difficulty faced with at the beginning of a trial to the difficulty presented after the stepwise change. To reduce its predictability, changes occurred between the fifth and eighth symbol of a sequence. In our analysis trials were merged relative to this change. In the remainder we will refer to *relative position 1* as the first symbol with new gap size.

Experiment 2 was the same as Experiment 1 except for a gaze-contingent display manipulation (McConkie & Rayner, 1975). In each trial the fixated symbol was visible to a participant, while all other symbols were masked by Xs. As soon as the eyes moved to the next stimulus, the previously fixated symbol was masked and the newly fixated symbol revealed. The gaze-contingent display technique was used to analyze the specific influence of foveal processing on the adjustment of fixation durations, since preview of upcoming symbols was prevented. By applying this manipulation, modulations of fixation durations can unambiguously be attributed to fixated stimulus elements.

4.4.2 Specific model assumptions for the scanning task

4.4.2.1 Saccade initiation intervals and processing

The decision *when* to initiate a new saccade program is generated by the ICAT model as described above. The rate $\omega_j(t)$ of the corresponding random walk j at time t is given by the number of states N_t and its average duration T_j (see Eq. 4.2). While we assume that the number of states N_t is constant over time, mean duration T_j varies with fixation history and depends on the expected processing difficulty A_j during fixation j . The expected processing difficulty A_j is estimated from experienced processing difficulty during previous fixations (see Eq. 4.6). For simplicity, we confine the influence of fixation history to the last symbol, i.e.,

$$A_j = \begin{cases} A_l & \text{if the last processed symbol had a large gap} \\ A_s & \text{if the last processed symbol had a small gap} \end{cases} \quad (4.24)$$

Mean duration T_j of a random walk depends on the expected processing difficulty A_j (see Eq. 4.7). Since we used only two different distractors in our experiment, we decided to estimate mean durations T_l and T_s for each symbol separately, i.e.,

$$T_j = \begin{cases} T_l & \text{for expected difficulty } A_l \\ T_s & \text{for expected difficulty } A_s \end{cases} \quad (4.25)$$

For a continuum of stimulus elements with varying target-distractor similarities (or a continuum of word difficulties during reading), a mathematical relation between the maximum of the activation, A_j , and the corresponding mean duration T_j can be estimated (see Eq. 4.7). In general, higher expected processing difficulty A_j will cause longer first-passage times of the random walk.

4.4.2.2 Target selection and mislocated fixations

Since our experiments are one-dimensional scanning tasks, we limited spatial aspects of our model to the horizontal component. In both experiments, saccades aimed at the center of the target symbol, i.e., $l_I = \chi_{tar}$ (see Eq. 4.19). Thus, generating a preference to fixate on an object in order to minimize processing time of the fixated stimulus. Because of systematic and oculomotor error actual saccade targets deviate from intended saccade targets. Due to the mislocated fixations mechanism, large deviations immediately initiate a new saccade program at the beginning of a fixation to correct for the observed deviation. The relation between landing site and intended saccade target for both experiments is visualized in Figure 4.12. When saccades land on the intended target stimulus probability of programming a corrective saccade is minimal. However, with increasing distance to a symbol's center the probability increases until a corrective saccade is almost always initiated when saccades land in the center of two adjacent stimulus elements.

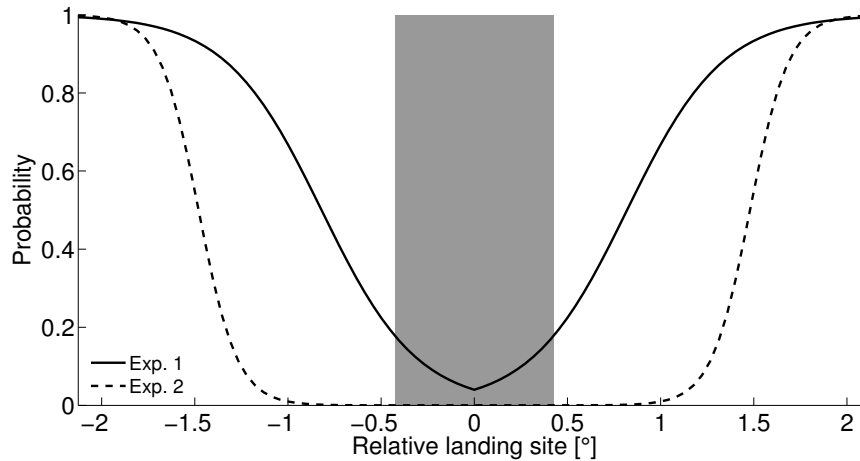


Figure 4.12: Probability of immediately initiating a new saccade program as a function of the landing site's distance to the target symbol's center. The gray area represents the position and size of the targeted stimulus.

4.4.2.3 Modeling gaze-contingent displays

In Experiment 2, the activation A_x of a masked stimulus element was limited to the processing difficulty A_s . Since identification of masked stimulus elements was impossible, processing did not enter the second (decreasing) stage when the maximum was reached. Instead, the activation remained at the maximum value, $a_n(t) = A_x$, until the stimulus was fixated by the model. When the fixation of a masked stimulus started, its activation was reset to zero (since parafoveal preprocessing was precluded by the mask), $a_k(t) = 0$, and processing was re-started.

4.4.3 Estimation of model parameters

We determined the free model parameters using a *genetic algorithm* approach (Holland, 1992; Mitchell, 1996), which was successfully applied to the SWIFT model (Engbert et al., 2005). For Experiment 1, we estimated 13 free parameters. Five additional parameters, average duration of the labile and non-labile saccade programming stages, τ_{lab} and τ_{nlab} , average duration of a saccade, τ_{ex} , number of oculomotor states, N_o , as well as a parameter for target selection, γ , were fixed prior to the estimation process. In Experiment 2 another four parameters were fixed to values estimated in the first experiment: Processing difficulty of easy and difficult stimuli, A_l and A_s , the preprocessing factor f , and the global decay parameter κ . For both experiments we estimated parameters using half of the subjects and assessed the quality of simulations with the second half.

For simulations of Experiment 1 performance of the model was evaluated (i) for durations of the first fixation on a stimulus, (ii) the duration of the n th fixation relative to a change, (iii) proportion of forward saccades, refixations, and skipings, (iv) distribution of first fixations on a stimulus, (v) modulations of fixation durations and refixation rate by fixation position within a stimulus. A list of estimated parameters is presented in Table 4.2 containing the best fitting set of parameters, mean, and standard error. Additionally, Table 4.2 informs about the range of possible parameter values submitted to the genetic algorithm.

Table 4.2: Model parameters: Experiment 1

| Parameter | Symbol | Best | Mean | Error | Min | Max | Reference |
|------------------------------------|---------------|--------|--------|--------|-------|-------|-----------|
| Processing parameters | | | | | | | |
| Activation (Large gap) | A_l | 110.41 | 111.81 | 2.10 | 30.0 | 130.0 | Eq. 4.24 |
| Activation (Small gap) | A_s | 230.11 | 230.11 | < 0.01 | 30.0 | 520 | Eq. 4.24 |
| Visual processing | | | | | | | |
| Visual span (right) | σ_R | 3.47 | 3.47 | < 0.01 | 1.0 | 7.0 | Eq. 4.13 |
| Visual span (left) | σ_L | 1.69 | 1.68 | < 0.01 | 0.0 | 7.0 | Eq. 4.13 |
| Global decay | κ | 0.26 | 0.26 | < 0.01 | 0.0 | 1.0 | Eq. 4.15 |
| Preprocessing | f | 50.33 | 50.26 | 0.78 | 1.0 | 100.0 | Eq. 4.15 |
| Saccade timing | | | | | | | |
| Timer states | N | 75.00 | 83.22 | 5.79 | 2.0 | 120.0 | Eq. 4.2 |
| Duration ^a (Large gap) | T_l | 205.81 | 241.50 | 0.34 | 150.0 | 250.0 | Eq. 4.25 |
| Duration ^a (Small gap) | T_s | 241.55 | 237.26 | 0.47 | 150.0 | 310.0 | Eq. 4.25 |
| Foveal inhibition | α | 0.19 | 0.19 | < 0.01 | 0.0 | 0.5 | Eq. 4.4 |
| Foveal inhibition | β | 3.40 | 3.40 | < 0.01 | 1.0 | 10.0 | Eq. 4.4 |
| Saccade programming | | | | | | | |
| Oculomotor states | N_o | 20.00 | | | | | Eq. 4.10 |
| Duration ^a (Labile) | τ_{lab} | 125.00 | | | | | Eq. 4.10 |
| Duration ^a (Non-labile) | τ_{nlab} | 40.00 | | | | | Eq. 4.10 |
| Duration ^a (Execution) | τ_{ex} | 25.00 | | | | | Eq. 4.10 |
| Target selection weight | γ | 0.10 | | | | | Eq. 4.16 |
| Mislocated fixations | ν_1 | 1.94 | 2.02 | 0.17 | 0.5 | 5.0 | Eq. 4.23 |
| Mislocated fixations | ν_2 | -0.82 | -0.82 | < 0.01 | -3.0 | 0.5 | Eq. 4.23 |

^aAll durations are presented in ms.

Table 4.3: Model parameters: Experiment 2

| Parameter | Symbol | Best | Mean | Error | Min | Max | Reference |
|------------------------------------|---------------|--------|--------|--------|-------|-------|-----------|
| Processing parameters | | | | | | | |
| Activation (Large gap) | A_l | 110.41 | | | | | Eq. 4.24 |
| Activation (Small gap) | A_s | 230.11 | | | | | Eq. 4.24 |
| Visual processing | | | | | | | |
| Visual span (right) | σ_R | 2.15 | 2.15 | < 0.01 | 0.0 | 7.0 | Eq. 4.13 |
| Visual span (left) | σ_L | 1.66 | 1.66 | 0.01 | 0.0 | 7.0 | Eq. 4.13 |
| Global decay | κ | 0.26 | | | | | Eq. 4.15 |
| Preprocessing | f | 50.33 | | | | | Eq. 4.15 |
| Saccade timing | | | | | | | |
| Timer states | N | 20.00 | 20.32 | 0.32 | 2.0 | 120.0 | Eq. 4.2 |
| Duration ^a (Large gap) | T_l | 307.91 | 306.93 | 0.49 | 280.0 | 360.0 | Eq. 4.25 |
| Duration ^a (Small gap) | T_s | 320.34 | 320.14 | 0.91 | 280.0 | 390.0 | Eq. 4.25 |
| Foveal inhibition | α | 0.05 | 0.05 | < 0.01 | 0.0 | 0.1 | Eq. 4.4 |
| Foveal inhibition | β | 4.35 | 4.35 | 0.04 | 0.0 | 10.0 | Eq. 4.4 |
| Saccade programming | | | | | | | |
| Oculomotor states | N_o | 20.00 | | | | | Eq. 4.10 |
| Duration ^a (Labile) | τ_{lab} | 125.00 | | | | | Eq. 4.10 |
| Duration ^a (Non-labile) | τ_{nlab} | 40.00 | | | | | Eq. 4.10 |
| Duration ^a (Execution) | τ_{ex} | 25.00 | | | | | Eq. 4.10 |
| Target selection weight | γ | 0.10 | | | | | Eq. 4.16 |
| Mislocated fixations | ν_1 | 4.81 | 4.94 | 0.65 | 0.5 | 6.0 | Eq. 4.23 |
| Mislocated fixations | ν_2 | -1.48 | -1.49 | 0.02 | -3.0 | 0.5 | Eq. 4.23 |

^aAll durations are presented in ms.

Simulations of Experiment 2 were evaluated by comparing model simulations with a) mean first-fixation durations on a stimulus, b) distributions of first-fixation durations at relative position 1, c) proportion of forward saccades and refixations, and d) mean fixation durations relative to the symbol center as well as corresponding refixation rates. Estimated parameters are presented in Table 4.3.

From the perspective of minimal modeling, we aim at a model with as few parameters as possible. Fortunately, statistical models of oculomotor errors do not require additional free parameters, since all parameters in Equations 4.20 and 4.21 can be estimated from experimental data (McConkie et al., 1988). However, four parameters ($l_l, \delta_{SRE}, \delta_0, \delta_1$) have to be estimated separately for forward saccades, forward and backward refixations, skippings, and regressions. Table 4.4 summarizes parameter combinations for Experiment 1 and Experiment 2, respectively.

4.4.4 Experiment 1: Stepwise processing change during visual search

In both experiments we investigated the behavioral response to a stepwise changes of processing difficulty by manipulating target-distractor similarity. We presented the entire search array at the beginning of a trial in Experiment 1. In the two baseline conditions

processing difficulty remained constant during a trial, i.e., all stimulus elements had either large gaps (low difficulty) or small gaps (high difficulty). Two further conditions explored fixation duration control while processing demands increased or decreased (Appendix 4.7).

4.4.4.1 Results I: Mean fixation durations

Average durations of the first fixation on a stimulus are plotted in the left panel of Figure 4.13. Stimulus position 1 corresponds to the first distractor with new gap size in conditions with varying processing demands (cf., Fig. 4.11). Since the absolute position of a change varied across trials, fixation durations in baseline conditions were selected accordingly. First-fixation durations are typically higher on more demanding stimulus elements (black solid vs. gray solid line) than on easy stimulus elements. When processing demands increase, an immediate prolongation of fixation durations is observed (gray dashed line). Decreasing processing demands by contrast produce a delayed response (black dashed line). While fixation durations on the first stimulus remain almost as long as the difficult baseline condition, first-fixation durations on subsequent stimulus elements slowly approach the low difficulty baseline.

Simulation results are shown in the central panel of Figure 4.13. The overall pattern is captured by the model. In order to assess the quality of simulations, we plotted simulated data against experimental data in the right panel of Figure 4.13. Filled dots show the relation between simulated data and the data points used to estimate model parameters (first half of participants). Gray squares represent the second half of participants predicted by the same simulations, however, corresponding data were not used for parameter estimation. Data points from the first and second half are connected by vertical lines. The unity line ($y = x$) was added to facilitate comparisons of experimental and simulated data. Data points based on a perfect prediction would line up on this reference line. Furthermore, we calculated correlation coefficients (Spearman rank correlation) between the first and the second half of the data (R_d), between simulated data and the first half (R_1), and between simulated data and the second half (R_2). The correlation coefficient R_d is an estimate of the reliability of the experimental data and gives an upper boundary of how well the model might predict experimental data. The value R_1 0 indicates how well

Table 4.4: Model parameters for oculomotor control

| Experiment | Saccade type | l_I | σ_G | δ_0 | δ_1 |
|--------------------|---------------------|-------|------------|------------|------------|
| 1: Stepwise change | Forward saccade | 4.20 | 0.25 | 0.65 | 0.05 |
| | Forward refixation | 1.90 | 0.25 | 0.65 | 0.05 |
| | Backward refixation | 1.00 | 0.25 | 0.65 | 0.05 |
| | Regression | 5.40 | 0.00 | 0.65 | 0.15 |
| | Skipping | 9.00 | 0.25 | 0.65 | 0.05 |
| 2: Gaze-contingent | Forward saccade | 4.20 | 0.85 | 0.45 | 0.006 |
| | Forward refixation | 0.90 | 0.6 | 0.45 | 0.006 |
| | Backward refixation | 0.75 | 0.70 | 0.45 | 0.006 |
| | Regression | 0.00 | 0.00 | 0.45 | 0.015 |

the model predicts the data used for parameter estimation. The value R_2 should not be considerably smaller than R_1 since deviations indicate an overfit of the model to the first half of participants. As can be seen in Figure 4.13 first and second half of the experimental data are quite similar and show a high correlation ($R_d = .87$). The correlation between simulated and experimental data are somewhat smaller but comparable in size ($R_1 = .74$, $R_2 = .77$). We provide correlational plots for all analyses to give an estimate of the quality of the simulated data. Generally, we did not observe overfitting of the data set used for parameter estimation.

Two aspects of the experimental data are worth highlighting. First, in the decreasing difficulty condition, fixation durations on the last difficult stimulus (relative position 0) are increased relative to the high difficulty baseline. Thus, even though the upcoming change decreases processing demands, fixation durations rise. A similar finding, the *parafoveal-on-foveal effect*, has been reported in word recognition (Kennedy, Pynte, & Ducrot, 2002) and reading (Inhoff, Starr, & Shindler, 2000) where properties of the next (parafoveal) word modulate fixation durations on the fixated (foveal) word. The increased fixation duration at position 0 lends support to such a parafovea-on-fovea effect in our data. However, in a first-order approximation, we did not include this effect in our model since its origin remains nebulous. Further research is needed to determine whether this is a real effect on saccade initiation intervals or just a consequence of additional saccade programming time because of, for example, readjusting average saccade length. Irrespective of the origin of the effect, our experimental results demonstrate that parafoveal processing is a crucial factor influencing fixation durations.

Second, saccade timer adjustments in our model depend on the last stimulus. Thus, a stepwise adjustment of fixation durations might be expected. Nonetheless, we observed a gradual decline of fixation durations across several stimulus elements in both experiment and model (dashed black line). Since eye movements are not constrained to strictly serial, left-to-right movements, items can be skipped without receiving a fixation. On some

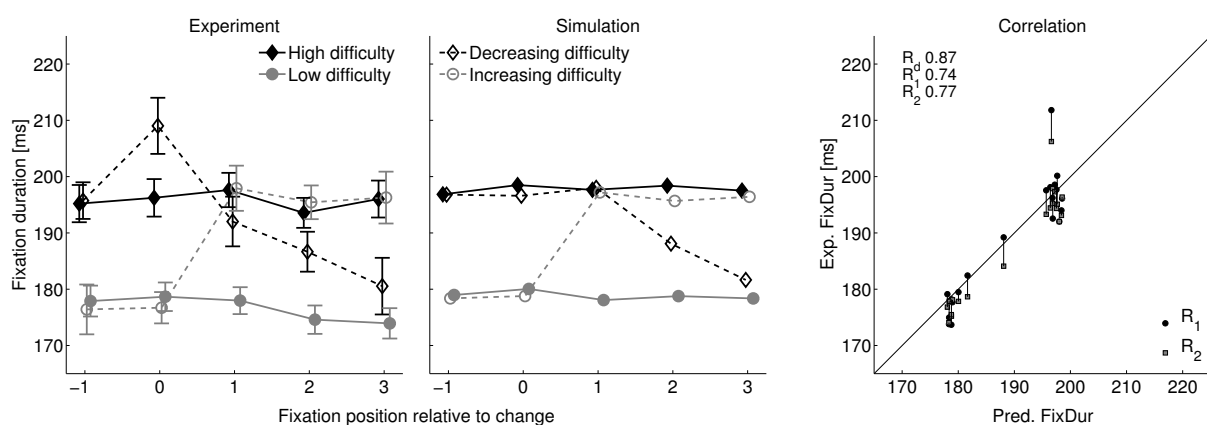


Figure 4.13: Mean first-fixation durations on a stimulus relative to a change in processing difficulty. Left panel: Experimental data; central panel: Simulation results. Solid lines represent baseline conditions without a change in gap size. In other conditions gap size changed at position 1 (dashed lines). Trials starting with stimulus elements with a small gap are plotted in black and trials starting with a large gap are plotted in gray. Right panel: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

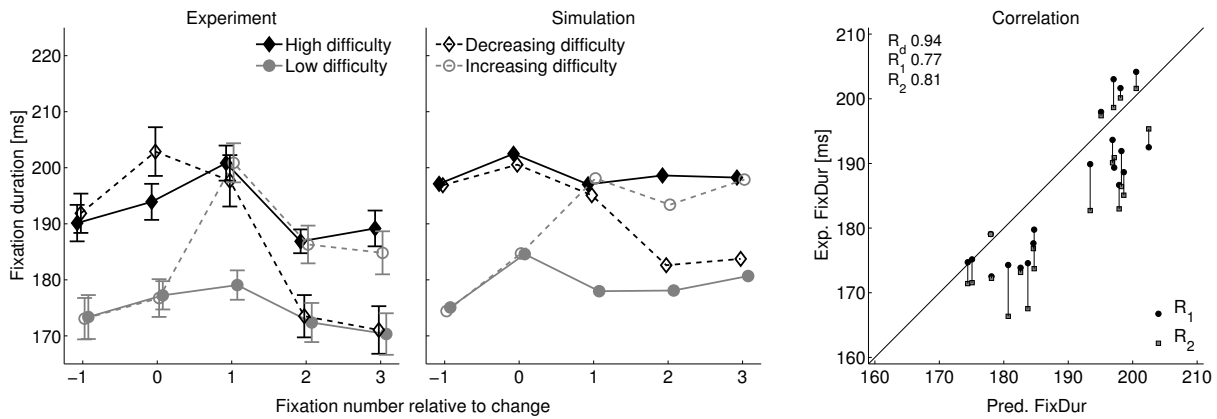


Figure 4.14: Mean fixation durations of the n th fixation relative to a change in gap size. Left panel: Experimental data; central panel: Simulation results. Solid lines represent baseline conditions without a change in gap size. In other conditions gap size changed at position 1 (dashed lines). Trials starting with stimulus elements with a small gap are plotted in black and trials starting with a large gap are plotted in gray. Right panel: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

occasions skippings will move the eyes from a simple stimulus to a difficult one that, in this case, already is the second or third stimulus after a change. Since saccades are more likely to skip a single stimulus, the proportion of skippings landing on the second stimulus is higher than the proportion of skippings landing on the third stimulus. When analyzing the n th fixation duration relative to the first fixation after a change, fixation durations show the expected modulations (Fig. 4.14). Increasing processing demands immediately prolong fixation durations, while decreasing processing demands lead to a reduction of fixation durations with a temporal delay. Both experimental and simulated data are well-adjusted on the second fixation after a change. Thus, the slow decline in Figure 4.13 is due to a mixture of forward saccades and skipping saccades.

4.4.4.2 Results II: Fixation duration distributions

Histograms of fixation durations with a binwidth of 25 ms are shown in Figure 4.15 for experimental (left panels) and simulated data (central panels). Distributions depict the first-fixation duration on a new stimulus (position 1), the preceding stimulus (position 0), and the two subsequent stimulus elements (positions 2 & 3). Experimental variability is well-captured by simulations of the full model. Each distribution was calculated by collapsing data across participants. We used the same fixations as in Figure 4.13 and fixation duration distributions evolve accordingly. On all stimulus elements fixation duration distributions are shifted towards longer fixations in the high difficulty baseline (black solid line) compared to the low difficulty baseline (gray solid line). At position 1, fixation duration distributions immediately resemble the high difficulty baseline when processing difficulty increases (gray dashed line). Decreasing processing difficulty (black dashed line), by contrast, generates a delayed (position 1) and gradual adjustment towards the low difficulty baseline (positions 2, 3). Inspection of the correlation plots reveals that both halves of the experimental data are well predicted by our model simulations.

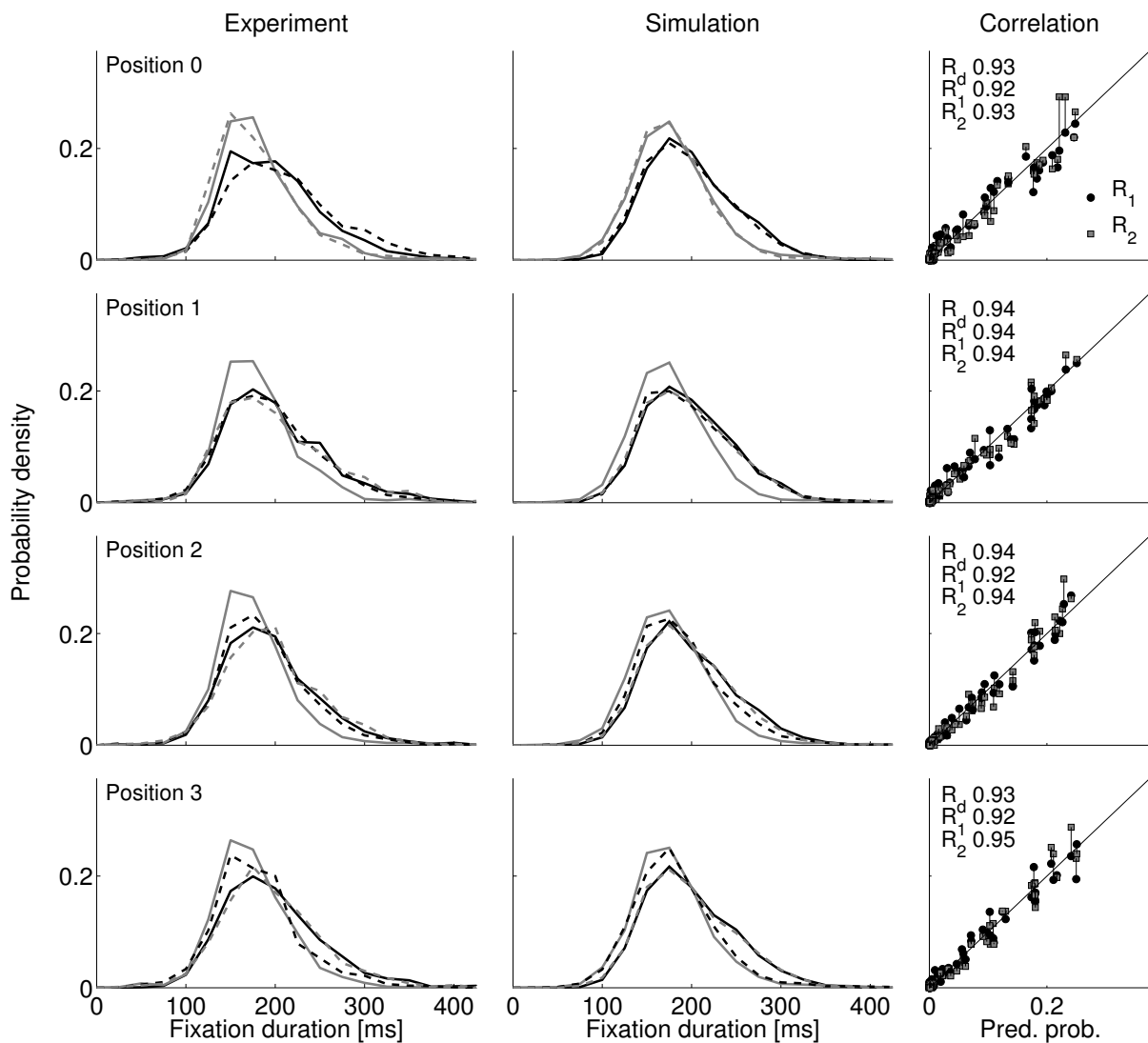


Figure 4.15: First-fixation duration distributions. Top panel: Histograms before a change (relative position 0); second panel: Histograms immediately after a change (relative position 1); bottom panels: Histograms after adjustment (relative positions 2, 3). Solid lines represent baseline conditions without a change in gap size. In other conditions gap size changed at position 1 (dashed lines). Trials starting with stimulus elements with a small gap are plotted in black and trials starting with a large gap are plotted in gray. Left panels: Experimental data; central panels: simulation results; right panels: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

4.4.4.3 Results III: Saccade type probabilities

The main focus of the ICAT model is to provide a framework for the control of fixation durations. Nevertheless, it is important to consider both temporal and spatial dynamics of eye movements. Figure 4.16 shows the proportion of forward saccades (top panels), skippings (middle panels), and refixations (bottom panels) after the initial fixation of a stimulus. In the high difficulty condition, participants generate more forward saccades and refixations as well as less skippings than in the low difficulty condition (black solid lines vs. gray solid lines). The same qualitative behavior is produced in our model simulations. The difference between both conditions, however, is less pronounced. When

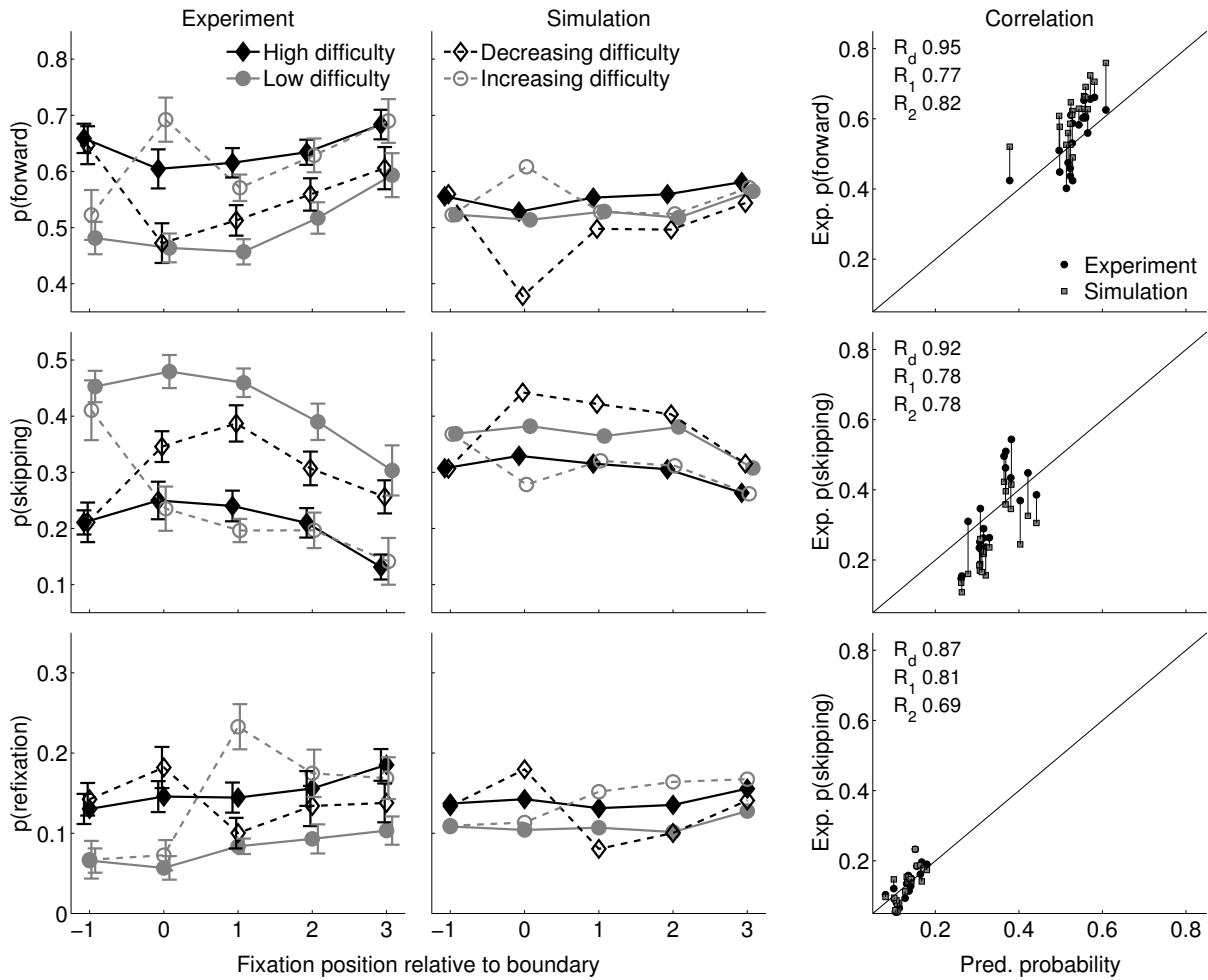


Figure 4.16: Probability of forward saccades (top panels), skippings (central panels), and refixations (bottom panel) relative to the change in gap size. Left panels: Experimental data; central panels: Simulation results. Solid lines represent baseline conditions without a change in gap size. In the remaining conditions gap size changed at position 1 (dashed lines). Trials beginning with a fixation on a stimulus elements with a small gap are plotted in black and trials beginning with a fixation on a large gap are plotted in gray. Right panels: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

processing demands change (dashed lines), the proportion of forward saccades, skippings, and refixations varies relative to the new stimulus difficulty as early as on the last stimulus before a change (position 0). As in the experimental data, target selection of the model adapts on the last stimulus before a change. Thus, in both the experimental data and the model simulations parafoveal preview is utilized for target selection. The model captures some of the qualitative findings of target selection. However, as can be seen in the correlation plots, systematic deviations from the experimental data are generated. Since the focus of our model is the control of fixation durations, we believe that the spatial behavior is sufficiently reproduced.

4.4.4.4 Results IV: Oculomotor control

During visual search, a substantial proportion of variability in oculomotor behavior is related to the fixation position within the fixated stimulus (Trukenbrod & Engbert, 2007).

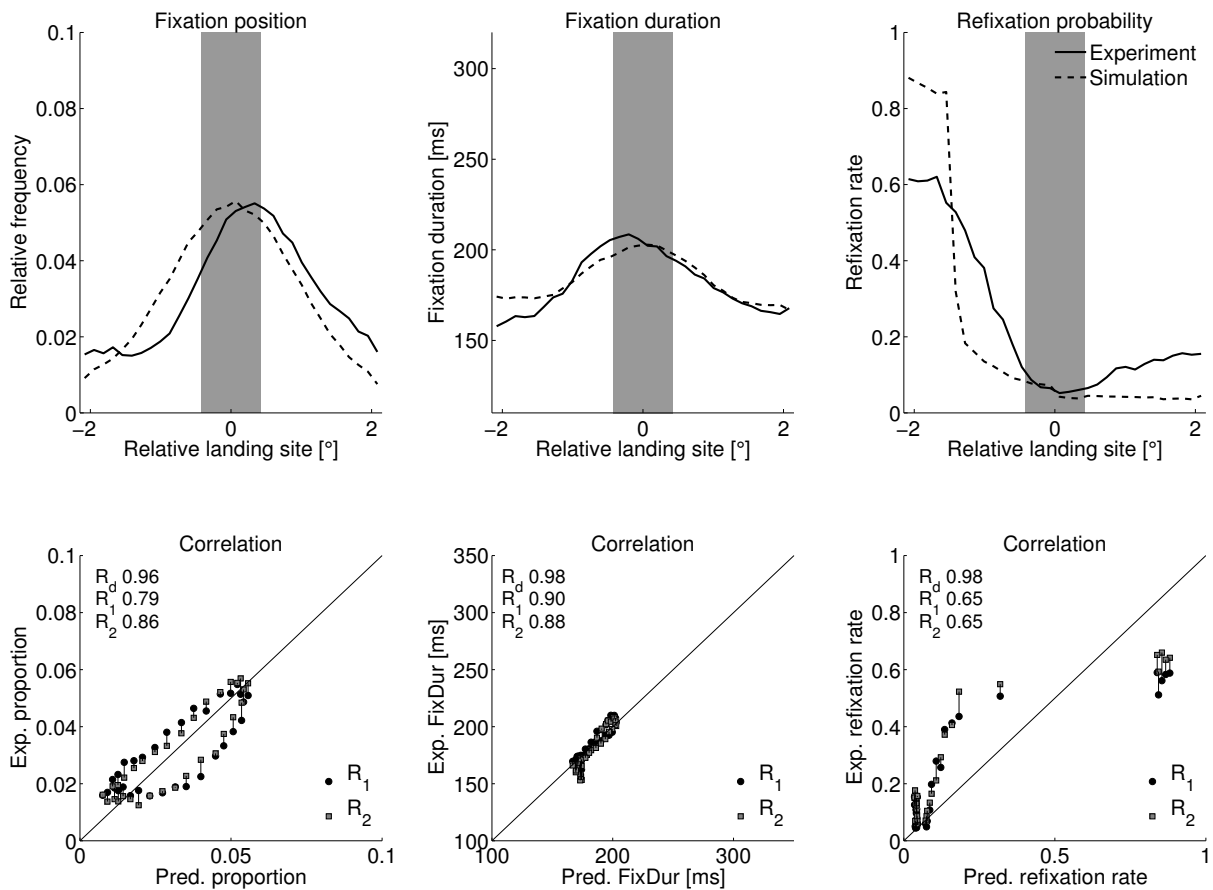


Figure 4.17: Oculomotor control: Effects of fixation position. Upper panels: In each plot, the horizontal axis represents the fixation position relative to the center of the fixated stimulus element. Solid lines indicate observed experimental data, simulated data are plotted with dashed lines. Left panel: Distribution of fixation positions; central panel: Fixation durations; right panel: Refixation probability. Lower panels: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

Since our task is a one-dimensional scanning task, we restricted our analysis to the horizontal component. Distributions of fixation positions, mean fixation durations, and refixation probabilities relative to the center of the fixated stimulus element are shown in Figure 4.17 (upper panels). The spatial extension of the fixated stimulus is indicated by the gray area in each of the sub-plots. Experimental data indicated by solid lines and simulation results are given by dashed lines. All results were averaged across conditions, different stimulus elements, and participants.

Experimental and simulated landing site distributions are shown in the left panel of Figure 4.17. First fixations on a stimulus were generally close to its center with some variability around this preferred fixation position. Since saccades aimed at the center of stimulus elements in our model, landing sites are shifted leftward in comparison to the experimental data. Comparing both distributions reveals that a simple mechanism that always targets at the center of a stimulus roughly approximates fixation positions in this task. Nevertheless, a more sophisticated targeting mechanism seems necessary to account for the systematic shift of the landing site distribution.

Next, we inspected fixation durations at different fixation positions (central panel in Fig. 4.17). Fixation durations decrease towards word edges during reading (Vitu et al. (2001; see also Nuthmann et al., 2005, 2007) or with increasing distance to the center of a stimulus in visual search (Trukenbrod & Engbert, 2007). The same relation can be observed in both our experiment and model. Fixation durations peak close to the center of a stimulus and decrease with increasing distance to the symbol. This qualitative behavior is predicted by the hypothesis that mislocated fixations are more frequently placed at word edges, where the triggering of error-correcting saccade induce a decrease in fixation durations. Fixation durations reach an asymptote of about 150–175 ms as a function of the distance from the center of the fixated symbol. The asymptotic value of duration corresponds to the minimum programming time of a saccade and suggests that the decision to initiate a new saccade at this location is made at the beginning of a fixation and is independent of the visual input as predicted by the efference copy assumption discussed above.

Finally, we investigated the probability of refixating a stimulus depending on the fixation position within an object (McConkie et al., 1989; Trukenbrod & Engbert, 2007). Refixation rate is asymmetrically affected by relative fixation position. The probability to refixate a stimulus is highest when fixations are left of the stimulus and decreases towards the symbol. After reaching a minimum rate close to the center of the stimulus, refixation rate right of a stimulus increases moderately. Model simulations reveal a qualitatively similar trend. However, simulations show a much steeper decline from the left to the right and no increase to the right of the center. Compared to other oculomotor effects, the probability of refixations is rather poorly captured. This is also evident in the correlation plot revealing systematic deviations for first and second half of the experimental data.

4.4.4.5 Results V: Skippings benefits

In well-structured tasks like reading or in the current experiment, processing order of objects is intrinsically given and saccades may be classified according to their target. In particular, the distinction between forward saccades, i.e., movements from the currently fixated object n to the neighboring object $n + 1$, and skippings, i.e., saccadic movements skipping the next object and moving gaze to a more distant object $\geq n + 2$, is impossible in less structured tasks but very informative in regard to eye guidance. Since skippings generate larger saccade amplitudes more information needs to be processed on fixations encompassing a skipping. Interestingly, the investigation of fixation durations has led to the observation of skipping benefits, i.e., shorter fixation durations before skipping the next object than before fixating the next object. Skipping benefits have been reported in scanning tasks (Trukenbrod & Engbert, 2012) and during reading, where they are mediated by word frequency or word length (Kliegl & Engbert, 2005). Furthermore, when looking for compensatory effects, Trukenbrod and Engbert (2012) demonstrated that at least some skippings are not accompanied by additional processing time on neighboring fixations.

Fixation durations before refixations, forward saccades, and skippings taken from the two baseline conditions (high difficulty, low difficulty) are plotted in Figure 4.18. Shortest fixation durations were observed before refixations both in the experiment and in

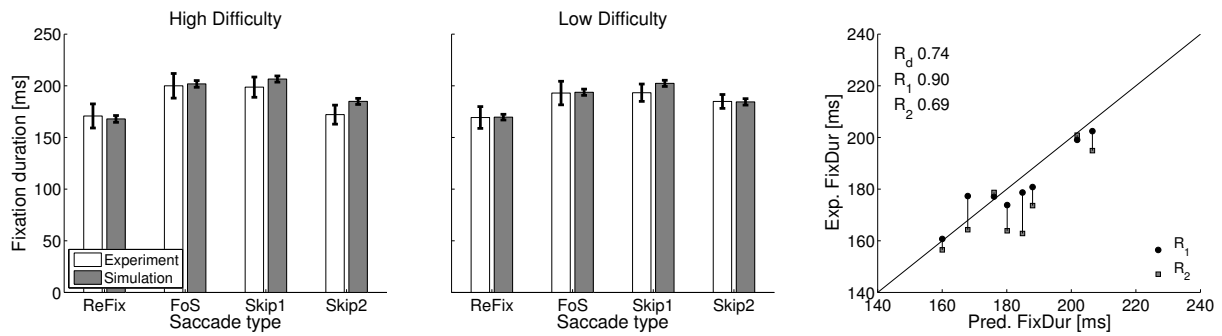


Figure 4.18: Experimental and simulated fixation durations before refixating an object, making a forward saccade towards the next stimulus, and skipping of the next (skipping 1) and next but one stimulus (skipping 2). Left panel: Fixations in the high difficulty condition; central panel: Fixations in the low difficulty condition; right panel: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

simulations. Skippings were further classified as saccades skipping one stimulus, landing on stimulus $n + 2$ (skipping 1), and saccades skipping two stimuli, landing on stimulus $\geq n + 3$ (skipping 2). Our experiment revealed skipping benefits that were attenuated in the low difficulty condition. Interestingly skipping more than one symbol resulted in shorter fixation durations than just skipping a single stimulus. Our simulations generate slightly longer fixation durations when the next stimulus is skipped. This effect, however, reverses when more than one stimulus is skipped and is attenuated in the low difficulty condition. Thus, saccades initiated by a timer that is modulated by processing but not triggered by processing is suitable to generate skipping benefits.

4.4.4.6 Summary: Experiment 1

The main purpose of Experiment 1 was to test the mechanisms of saccade timing underlying the ICAT model within a full model of eye guidance. Our simulation results demonstrate that effects of asymmetric control of fixation durations is compatible with spatial behavior of our model. While average fixation durations can immediately be prolonged when processing demands increase, a shortening of fixation durations is only observed on subsequent fixations. Variability produced by our model is comparable to the variability observed experimentally. Furthermore, the full eye-movement model mimics target selection on the level of different saccade types, landing sites within an object, as well as oculomotor behavior related to the landing site. Thus, the implementation of our control principles provides a realistic description of the spatio-temporal dynamics present in eye movements in a visual search task. In addition, analysis of skipping benefits revealed that saccade timing as implemented in our model does not necessarily generate prolonged fixation durations prior to skippings, contrary to models assuming sequential attention shifts (Engbert & Kliegl, 2011).

4.4.5 Experiment 2: Gaze-contingent display presentation

In Experiment 2 we developed a more rigorous test of foveal timing. We tested the same conditions and presented the same stimulus elements as in Experiment 1, however,

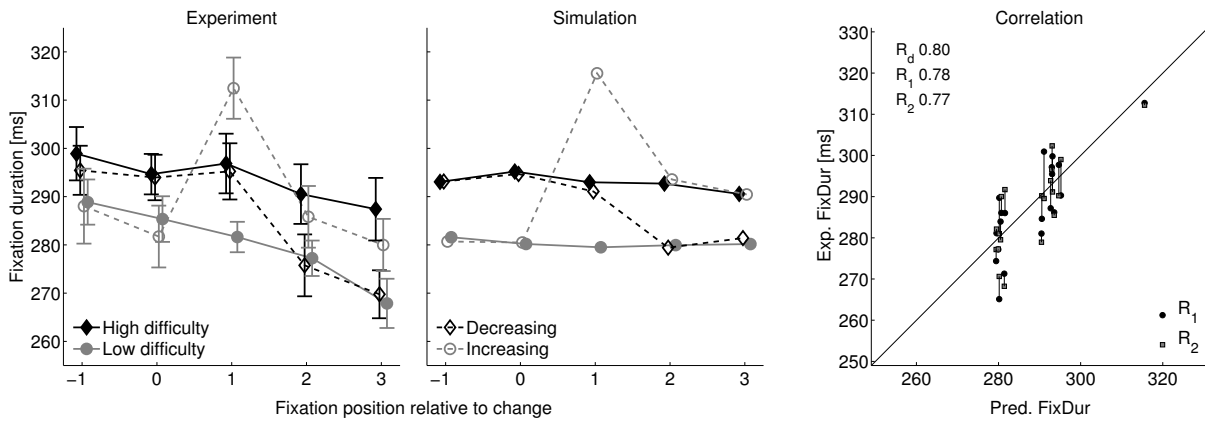


Figure 4.19: Mean first-fixation durations on a stimulus relative to a change in gap size. Left panel: Experimental data; central panel: Simulation results. Solid lines represent baseline conditions without a change in gap size. In other conditions gap size changed at position 1 (dashed lines). Trials starting with stimulus elements with a small gap are plotted in black and trials starting with a large gap are plotted in gray. Right panel: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

parafoveal preprocessing was precluded by masks (using an ‘X’ as mask). As soon as participants moved the gaze to a new object, the previously fixated stimulus was covered by the mask and the newly fixated stimulus was revealed. Since the task could only be solved successfully by fixating each stimulus element, we asked participants to scan arrays from left-to-right and to fixate each stimulus. Trials with skipings or regressions were excluded from further analyses.

4.4.5.1 Results I: Mean fixation durations

Results from the second experiment are plotted in the left panel of Figure 4.19. As in Experiment 1, durations of the first fixation on a stimulus were higher in the high processing difficulty condition (black solid line) than in the low difficulty condition (solid gray line). When processing demands decreased (black dashed line), fixation durations did not immediately adjust to the new stimulus element. Instead, fixation durations remained unchanged with respect to the difficult baseline condition. When processing difficulty increased (gray dashed line), an immediate but disproportionate prolongation of fixation durations was observed. Immediately after the increase fixation durations were longer than expected by the baseline condition consisting of difficult stimulus elements.⁷ In both conditions fixation durations returned to the corresponding baseline on the second stimulus element after a change.

Results from our simulations are shown in the central panel of Figure 4.19. Note that fixation durations across participants decrease with increasing position of the symbol. In our simulations we did not seek to account for this linear trend. Mean fixation durations were fit to mean durations at *relative position 1*. The qualitative pattern is in good agreement with the detrended experimental data. Fixation durations are longer when processing difficulty is high (black solid lines vs. gray solid lines). When processing

⁷A mask prevented preview of unfixated stimulus elements. Hence, processing time was the same in both conditions.

demands decrease, fixation durations remain long on the first stimulus with a large gap size and decrease only after the second fixation (dashed black line). Most interestingly, for increasing processing demands the model generates an immediate and disproportionate prolongation on the first difficult stimulus element and returns to the baseline on the second stimulus element (gray dashed line).

4.4.5.2 Results II: Fixation duration distributions

Histograms of the first-fixation durations on a symbol (position 1), before (position 0), and after a change (position 2) are plotted in Figure 4.20 (left panels: Experiment; central panels: Simulation; right panels: Correlation plots). Distributions of fixations on difficult symbols were shifted towards longer fixation durations (black solid line vs. gray solid line). This shift can be observed at all positions in the baseline condition. The empirical pattern is reproduced by the model simulations. When processing demands changed during a trial, distributions were differentially modulated by increasing and decreasing difficulty. Before a change, distributions matched the corresponding baseline conditions. Immediately after a change, fixation duration distributions were almost unaffected by decreasing processing difficulty (black dashed line). At the same time, increasing processing difficulty strongly modulated the shape of the fixation duration distribution (gray dashed line). Prolongation of fixation durations was accompanied by inflated variability. Thus, longer fixation durations after a change did not result from a shift of the distribution, but rather from a prolongation of long fixation durations (i.e., > 250 ms). Irrespective of the change, distributions on the second symbol after a change did not differ from the baseline conditions. Model simulations successfully reproduce the observed pattern across conditions and, most importantly, recover the distorted shape of fixation duration distributions when processing demands increase.

4.4.5.3 Results III: Saccade type probabilities

As for the first experiment, we examined target selection of our model. Probabilities to move from one stimulus to the next after its first fixation are plotted in Figure 4.21. Across positions we observe differences between conditions. These differences, however, are smaller and less reliable compared to the differences found in Experiment 1. In baseline conditions, forward saccades are more likely when fixating a simple stimulus (black solid line vs. gray solid line). For increasing processing demands, rate of forward saccades immediately drops after fixating the first difficult stimulus (gray dashed line). As observed in the pattern of fixation durations, this reduction is larger than expected by the baseline condition revealing a tendency to overcompensate for the increased processing demands. During target selection, however, this overcompensation seems to endure across multiple stimulus elements. In contrast, for decreasing processing demands (black dashed line), rate of forward saccades remains low for up to two stimuli after a change. Interestingly, neither the fixation duration nor the rate of forward saccades reflects decreased processing demands at position 1.

Simulation results are plotted in the central panel of Figure 4.21. As observed during the experiment, rate of forward saccades is lower on difficult stimuli (black solid line

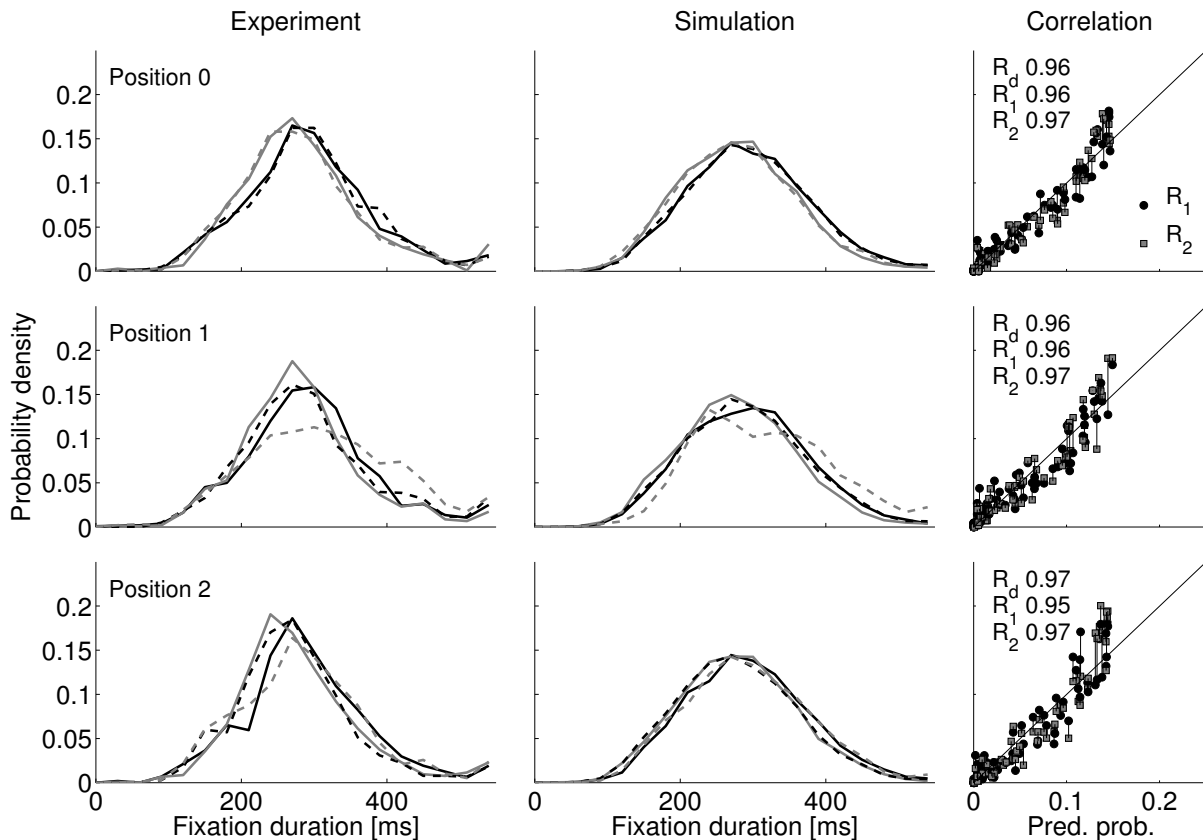


Figure 4.20: First-fixation duration distributions. Top panel: Distributions before a change (relative position 0); central panel: Distributions immediately after a change (relative position 1); bottom panel: Distributions after adjustment (relative position 2). Solid lines represent baseline conditions without a change in gap size. In other conditions gap size changed at position 1 (dashed lines). Trials starting with stimulus elements with a small gap are plotted in black and trials starting with a large gap are plotted in gray. Left panel: Experimental data; central panel: Simulation results; right panels: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

vs. gray solid line). When processing demands change, simulations show an immediate adjustment towards the new baseline condition. Hence, target selection in its current implementation is strongly based on moment-to-moment processing, but over- and underestimation of saccade probabilities confirms our conclusions from Experiment 1 that target selection is currently too simplistic to capture all details of saccade targeting.

4.4.5.4 Results IV: Oculomotor control

Finally, we also investigated oculomotor behavior related to the fixation position within an object. Horizontal landing site distributions are shown in the left panel of Figure 4.22. In general, initial landing positions are close to the center of a symbol with a narrow distribution around the fixated stimulus element. Model simulations nicely reproduce average landing site as well as its variability.

Fixation duration modulations relative to the fixated stimulus are shown in the central panels of Figure 4.22. As expected, fixation durations decrease towards adjacent stimulus elements. Compared to the first experiment, absolute effect size is much larger since

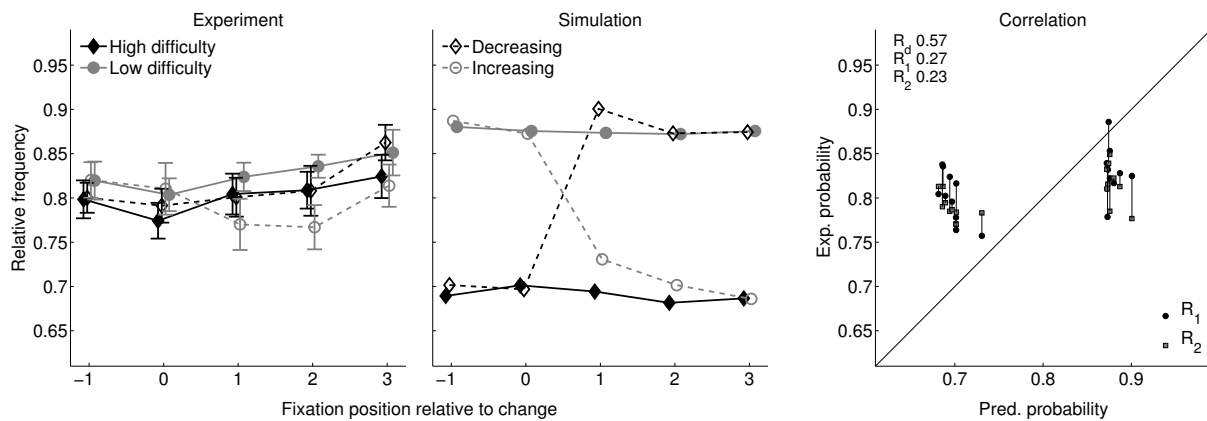


Figure 4.21: Probability of forward saccades relative to a change in gap size. Left panel: Experimental data; central panel: Simulation results. Solid lines represent baseline conditions without a change in gap size. In other conditions gap size changed at position 1 (dashed lines). Trials starting with stimulus elements with a small gap are plotted in black and trials starting with a large gap are plotted in gray. Right panel: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

fixation durations at the center rise from about 220 ms to approximately 300 ms in Experiment 2, while fixation durations beside the stimulus remain at around 150 ms in both experiments. Overall, the strong effect is replicated by our simulations. The current implementation, however, generates a symmetrical modulation leading to a weaker effect to the left of a stimulus and a stronger effect to the right of a stimulus.

In a final analysis we compared refixation rate within a stimulus. As observed in the previous experiment, refixation rate is asymmetrically affected by landing site. Refixation rate is highest left of the stimulus, decreases towards the center, and rises towards the right. Model simulations show the same qualitative behavior, but give just a rough approximation of the observed refixation rates.

4.4.5.5 Summary: Experiment 2

Experiment 2 was a gaze-contingent experiment focussing on the control of fixation durations solely by foveal information. The results confirmed an asymmetric control of fixation durations as proposed in this article. While increasing processing demands may immediately prolong fixations, decreasing processing demands will only affect fixation durations on subsequent fixations. Furthermore, simulations of a full eye-movement model captured temporal as well as spatial aspects of eye movements. Thus, control principles proposed in the ICAT model can be combined with target selection principles without disturbing spatio-temporal dynamics of eye movements.

4.5 General Discussion

We proposed and analyzed a new computational model for the control of fixation durations. We argued that the model explains experimental findings across tasks like reading, visual search, and scene perception within an unified framework. Our model is

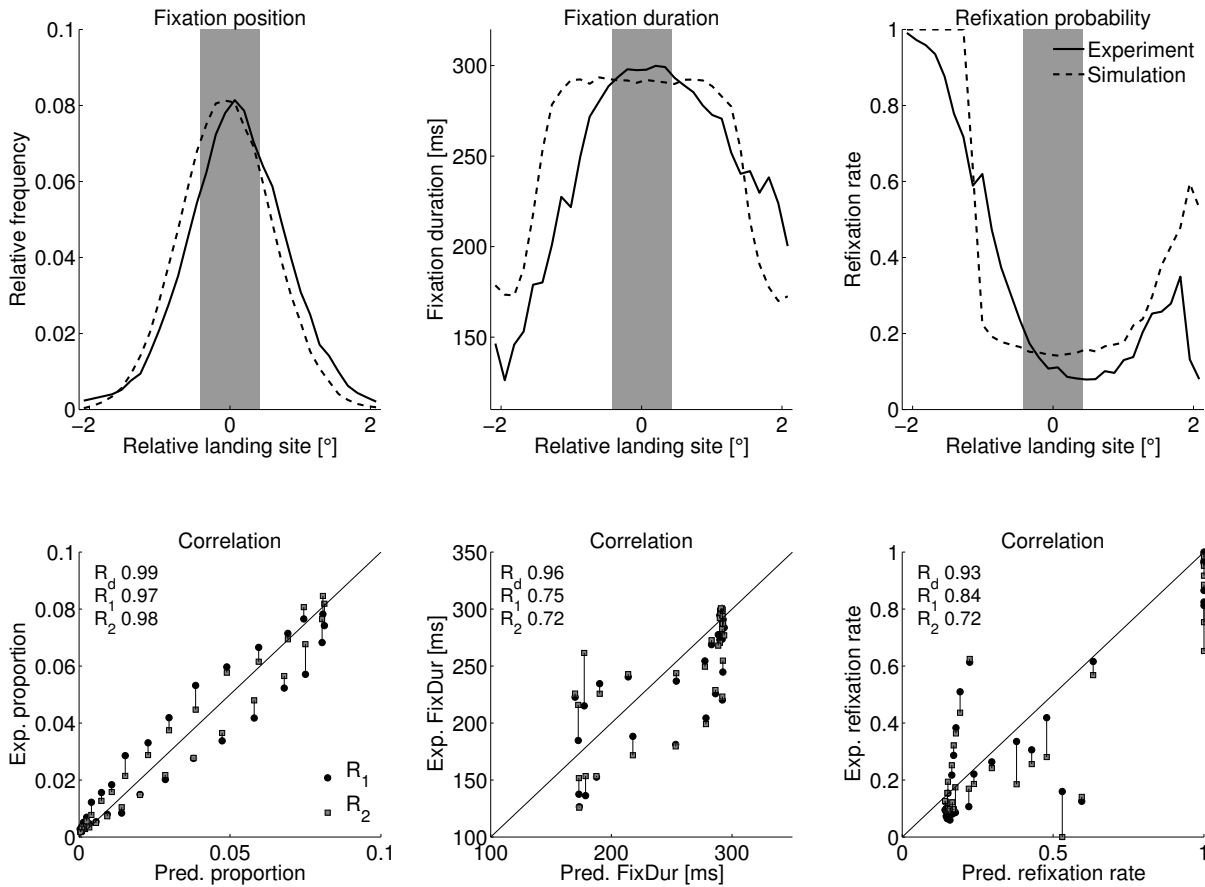


Figure 4.22: Oculomotor control: Effects of fixation position. Upper panels: In all plots, the x-axis represents the horizontal fixation position relative to the center of the fixated stimulus element. Solid lines show observed experimental data, simulated data are plotted with dashed lines. Left panel: Distribution of fixation positions; central panel: Fixation durations; right panel: Refixation probability. Lower panels: Comparison of simulations with first and second half of the experimental data. R_d gives the correlation between first and second half of the experimental data. R_1 and R_2 indicate correlations between simulated data and first half and second half, respectively.

based on three core principles. First, autonomous saccade timing initiates new saccade programs after random time intervals independent of processing during a fixation. Second, average durations of autonomous saccade timing are adjusted to expected foveal processing demands. Expectations are built up by the preceding fixation history. Third, foveal inhibition prolongs the initiation of a saccade program when processing is highly demanding. Foveal inhibition may have an immediate effect on fixation durations. Contrary to assumptions of cognitive trigger theories this process modulates fixation durations and is not the engine driving the eyes.

In a second part we evaluated performance of the model in two versions of a scanning task. Saccade initiation was incorporated into an existing model of eye-movement control during reading (i.e., SWIFT, Engbert et al., 2005). Simulations confirm that our model is able to reproduce the development of average fixation durations and corresponding distributions while simultaneously maintaining a realistic spatial control of eye movements. Furthermore, even though the framework for eye-movement control (the SWIFT model) was developed for text reading, the full model accounted for effects of target selection and was in good qualitative agreement with oculomotor control related

to fixation positions relative to the center of a fixated stimulus element. Furthermore, skipping benefits, i.e., shorter fixation durations before skipplings than before forward saccades, were replicated with ICAT. This effect has been suggested as a severe challenge for models assuming sequential attention shifts as the cognitive trigger for the control of fixation durations (Engbert & Kliegl, 2011).

4.5.1 Temporal adjustment of saccade timing

One outstanding characteristic of our model is the dynamic implementation of saccade initiation intervals based on the history of encountered processing demands. This is a crucial improvement with respect to previous theories about random saccade timing (Engbert et al., 2005; Hooge & Erkelens, 1998; Kolers, 1976), where saccade initiation intervals were assumed to be constant during a trial while matching overall task demands. In the latter case, saccade timing can only be adjusted when the difficulty is known and will not adapt to new processing demands during a trial. During everyday activities processing demands continuously vary within and across tasks with both gradual and abrupt changes and our saccadic system is constantly required to adapt to new situations. It seems that previously faced processing difficulty is a useful predictor for the time required for task-dependent analysis. However, fixation history and expectations were confounded in our experiment. Simulating reading data that investigated effects of contextual constraints (see Supplementary Information, simulation of the Staub, 2011, data set) revealed the importance of expectations independent of word properties. Thus, expectations in saccade timing are more than fixation history.

4.5.2 Foveal inhibition: Cognitive triggers vs. indirect control of fixation durations

Across tasks, there have been enduring debates whether fixation durations are controlled by cognitive triggers or under indirect control modulated by processing. This problem is particularly difficult to solve in complex tasks like reading, where fixation durations are affected by multiple factors. One major advantage of the proposed model is, that it allows to estimate the influence of processing on a moment-to-moment basis. Since immediate modulations of fixation durations can only be achieved by foveal inhibition, parameters of foveal inhibition uncover to which degree fixation durations depend on momentary processing. At one extreme, fixation durations will be unaffected by foveal inhibition. At the other extreme, foveal inhibition decreases the rate of the random walk on each time step. Hence, estimated parameters reveal whether fixation durations in a given task can be accounted for by a pure indirect control mechanism, or determine to which degree fixation durations are modulated by ongoing processing. Interestingly, all simulations reported here and in the Supplementary Information were based on parameter combinations leading to an asymmetric control. Even though some effects might seem like evidence for cognitive trigger theories (as frequency modulations during reading), asymmetric control seems to be sufficient to replicate the observed data patterns.

4.5.3 SWIFT and CRISP models

Our model extends the concept of random timing first proposed in SWIFT (Engbert et al., 2005), a model of eye-movement control during reading, and CRISP (Nuthmann et al., 2010), a model of eye-movement control in scene viewing. Both frameworks agree on core assumptions about saccade timing. Saccades are initiated after random time intervals by an autonomous saccade timer. Thus, an indirect control mechanism triggers new saccades. When encountering high processing demands, foveal inhibition delays saccade initiation. Both frameworks represent mixed control strategies since saccades are generated after random durations but can be modulated by ongoing processing. The presented model, however, contains substantial improvements.

First, temporal adjustments of saccade timing are explicitly implemented in our model. Saccade timing is a dynamic process and both autonomous initiation and foveal inhibition change over time as a function of fixation history. As mentioned earlier this is a novelty for models of eye-movement control. However, more research is needed to determine the number of fixations influencing saccade timing in different tasks. Saccade timing in SWIFT may be seen as an extreme case where parameters depend on an infinite number of preceding fixations. In this case, local changes in processing demands, will not affect random saccade timing. Instead, the average duration of the autonomous saccade timer and the strength of foveal inhibition remain constant during a task. Our model may help to estimate the maximum number of fixations influencing saccade timing and the sensitivity to local changes in processing demands during reading.

Second, continuous-time, discrete-state random walks control saccade initiation intervals and saccade programming. Mathematically, this implementation has at least two major advantages compared to the procedure used in SWIFT, where a set of coupled ordinary equations is discretized by the Euler method for the computation of numerical solutions. Simulations of our model with a Monte Carlo procedure proposed by Gillespie (1978) are mathematically exact and time-efficient, since each iteration step (with variable length) reflects a state change and numerical inaccuracies due to discretization are avoided. While CRISP uses a single random walk, our implementation demonstrates how multiple random walks can be simulated simultaneously.

Third, as in CRISP foveal inhibition is implemented on a moment-to-moment basis. By using continuous-time, discrete-state random walks for autonomous saccade timing, foveal inhibition can be implemented as a continuous process. In our model rates of a random walk are immediately modulated by ongoing processing. Depending on the strength of foveal inhibition a varying number of time steps are affected. As a consequence, foveal inhibition is able to generate miscellaneous fixation duration distributions and reproduces complex patterns.

4.5.4 Advantage of autonomous saccade timing

The control of fixation durations is an important aspect of eye-movement control across tasks. Saccade timing as proposed in this article generates realistic sequences of fixation durations. At the same time it overcomes some major constraints inherent to cognitive trigger theories. In this section we discuss four of these issues.

4.5.4.1 Temporal constraints

A crucial problem for cognitive trigger theories arises from temporal constraints of the visual system. Because of the eye-brain lag, it takes at least 50 ms for visual input to be transmitted from the retina to areas of visual cortex (Lamme & Roelfsema, 2000). Another 150–175 ms are required after the decision to initiate a saccade to actually execute it (Rayner, 1998). Average fixation durations are on the order of 200–300 ms in tasks like reading, visual search, or scene perception. If saccades are triggered by cognitive processing, only a short duration remains for the visual analysis of the fixated area. If profound processing takes place before initiation of a saccade, saccadic dead time is observed. In this case, visual input of the fixated area is useless after saccade initiation since the fixated area has already been analyzed and the fovea, the area of highest visual acuity, will be bound to an already processed area for another 150 ms.

In contrast, autonomous saccade timing is independent of visual input. Saccades are initiated after random time intervals which are estimated to be appropriate for the task. This account minimizes saccadic dead time. On average a fixated area will provide sufficient visual input until the next saccade is executed. At the same time, the eyes do not wait for a processing decision. However, in our model fixations can be prolonged by foveal inhibition if additional processing time is needed. Furthermore, since targets of the next saccade can be modified up to 50 ms before execution of a saccade (Becker & Jürgens, 1979), processing after the initiation of new saccade program may be used for eye guidance and additional processing time can easily be obtained by refixating the target area.

4.5.4.2 Voluntary saccade initiation and saccadic selectivity

While the oculomotor system is able to maintain fixations over long periods of time, saccade programming seems to be under less voluntary control. Donk and van Zoest (2008) instructed participants to direct an eye movement to the most salient stimulus. While participants were able to unequivocally identify the target, the proportion of saccades towards the most salient stimulus decreased over time. Moreover, even though fixation durations often vary across tasks, eye-movement parameters are not easily modulated by task instructions. In a direction-coded search task, participants were instructed to either perform a task as correctly or as fast as possible (Hooge & Erkelens, 1998). Under both conditions, fixation durations and saccadic error rates did not vary between instructions.

Both examples illustrate limitations of voluntary control in the saccadic system, but are compatible with saccadic control in our model. Saccades are initiated after random time intervals and saccade targets are selected based on a saliency map (Koch & Ullman, 1985) that develops over time. From this perspective, saccadic control is a dynamic process. The saliency map changes continuously and saccade targets depend on the time-point of target selection. After short fixation durations bottom-up saliency dominates the saliency map, whereas top-down control manifests itself in the long run. During visual search, this generates saccades towards stimulus elements sharing properties with the specified target after long fixations, while saccades after short fixations are executed unselectively (Hooge & Erkelens, 1999; L. G. Williams, 1967; Zelinsky, 1996).

4.5.4.3 A single mechanism for the control of fixation durations across tasks

Eye movements consist of a spatial and a temporal component. The resulting data set is highly complex and similar outcomes can be generated by very different eye-movement patterns. Additional processing time, for example, can be obtained by longer fixation durations as well as refixations. A realistic models of eye guidance needs to incorporate and evaluate both target selection and fixation durations to account for interactions in eye-movements patterns. Current models of eye-movement control during reading perform well on both components (e.g., Engbert et al., 2005; Reichle et al., 1998). However, the control of fixation durations has not been included in computational models in visual search (Najemnik & Geisler, 2005; Rutishauser & Koch, 2007; Zelinsky, 2008) or scene perception (Itti & Koch, 2001; Kienzle et al., 2009; Torralba et al., 2006; see Nuthmann et al., 2010 for an exception). The principles proposed in this article provide a suitable framework for the initiation of saccades across these tasks.

Furthermore, saccade timing in our model produces a continuum of behaviors from pure indirect control at one extreme to strong modulations by foveal inhibition (i.e., ongoing processing) at the other. From the perspective of our model saccade timing may vary between tasks as well as over the time course of a task. Differences in eye-movement patterns can be accounted for by differences in average saccade initiation intervals as well as strength of foveal inhibition. For example, during mindless reading foveal inhibition is expected to decrease and, as a result, frequency effects will attenuate. During skimming average saccade initiation intervals will be reduced and result in shortened fixation durations (Just & Carpenter, 1987). When a difficult question is presented at the end of a sentence, fixation durations increase during the next trial (Bohn & Kliegl, 2007) since parameters are reset to a more elaborate processing mode. Furthermore, autonomous saccade timing is a reasonable process to initiate saccades in the absence of processing as scanning of z-strings (Vitu et al., 1995; Rayner & Fischer, 1996; Nuthmann et al., 2005). Thus, our model can be applied to different tasks as well as a range of processing modes when inspecting the same stimulus material.

4.5.4.4 Variability of fixation durations

Thus far, temporal control of eye movements has primarily focused on average fixation duration patterns. Nonetheless, fixation durations are highly variable and models of eye-movement control should reproduce this variability. In sequences of saccades, distributions vary between fixations relative to an event (see condition with increasing difficulty in Experiment 2; or, e.g., Van Loon, Hooge, & Berg, 2002; Yang & McConkie, 2001). Our model produces realistic variability in fixation durations based on microscopic assumptions about a random-walk process (cf., SWIFT, Engbert et al., 2005; CRISP, Nuthmann et al., 2010). Moreover, modulations of fixation durations originate from a continuous interaction between ongoing processing and saccade timing. In this approach, the exact form of the distribution has not to be defined in advance (Beintema, Van Loon, & Van Den Berg, 2005).

4.5.5 Conclusions

Using a computational model, we studied principles of fixation duration control. First, random timing with adjustments to high processing difficulty by foveal inhibition is suggested as local control principles. Additionally, we introduced a global control for the adjustment of fixation durations to specific task constraints that are independent of the current processing difficulty. We demonstrated the applicability of our model to control fixation durations in tasks with sequences of fixations. The model reproduced both average fixation duration patterns as well as fixation duration distributions.

4.6 Acknowledgments

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4.7 Appendix: Experimental Details

4.7.1 Experiment 1: Stepwise change in processing demands

4.7.1.1 Participants

We tested 32 participants (23 female, 9 male), all students at the University of Potsdam, with an average age of 23 years ranging from 19 to 39 years. All subjects received study credits or were paid 9€ and reported normal or corrected-to-normal vision.

4.7.1.2 Task, stimuli, and procedure

Participants were instructed to scan sequences for a target symbol from left-to-right. Target presence and absence had to be indicated by making a saccade to the upper or lower right corner of the screen with response mapping being counterbalanced across participants. Responses were evaluated and errors caused a short beep at the end of a trial. We tested four conditions (Fig. 4.11). Stimulus elements in the baseline conditions had constant difficulty, while processing demands increased/decreased in the other conditions. Search arrays consisted of eleven horizontally arranged stimuli with a center-to-center distance of 4.32° . Changes occurred on the fifth to eighth stimulus and were equally likely at all four positions. There was only one change in trials with varying processing demands.

Targets were black rings with an absolute size of $.86^\circ$ and a line-width of $.23^\circ$ when presented in front of the participant at the center of the screen. We manipulated processing demands by varying target-distractor similarity with “easy” distractors having a larger gap than “difficult” distractors ($.14^\circ$ vs. $.05^\circ$). Gaps were located in one of four

cardinal positions (top, bottom, left, right) and all stimuli were presented on a light gray background.

Each trial started with the presentation of a small black fixation cross (each line: $.64^\circ \times .18^\circ$). Trials continued if both eyes remained within a fixation area centered around the cross ($1.77^\circ \times 1.77^\circ$) for 200 ms. After successful fixation the fixation cross disappeared and the search array was presented. The leftmost stimulus of the array was centered on top of the fixation cross. After scanning the sequence subjects indicated target presence/absence. The next trial started after response evaluation. Overall participants searched 256 trials. Targets were present in 25% of trials and the order of trials was randomized. Eye movements were recalibrated every fifteenth trial or when a fixation check failed three times in succession.

4.7.1.3 Apparatus

Stimulus presentation was controlled by an Apple Power Macintosh G3 computer and presented on a 22-in. Iiyama HM204DT CRT (resolution: 1024×768 , refresh rate: 100 Hz). We recorded eye movements using the video-based Eyelink-II system (SR Research, Osgoode, ON, Canada) with a sampling rate of 500 Hz and used a chin rest to reduce head movements. Stimulus presentation and response collection were implemented in MATLAB (The MathWorks, Natick, MA, USA) using the Psychophysics Toolbox (PTB2; Brainard, 1997; Pelli, 1997) as well as the Eyelink Toolbox (Cornelissen et al., 2002).

4.7.1.4 Data preprocessing

We limited our analyses to target-absent trials. Saccades were detected using a velocity-based algorithm developed by Engbert and Kliegl (2003; improved by Mergenthaler and Engbert, 2006). Saccades were detected whenever both eyes exceeded a velocity threshold in 2D velocity space (≥ 5 SD) for at least 6 successive data points (12 ms) with a minimum amplitude of 0.29° ($1/3$ symbol size). For each fixation we computed a mean fixation position and assigned it to the closest symbol. Trials with blinks or fixations outside the monitor were excluded from further analyses as well as fixations on the first and last stimulus of the array.

4.7.2 Experiment 2: Gaze contingent display presentation

4.7.2.1 Participants

30 persons (27 female, 3 male) participated in the experiment. Subjects were either pupils at a local school in Potsdam or students of the University of Potsdam. All received course credits or were paid 9€. On average participants were 21 years ranging from 15 to 34 years. All participants had normal or corrected-to-normal vision.

4.7.2.2 Task and stimuli

In the second experiment we limited processing to the fixated stimulus by presenting stimulus elements gaze-contingent. While the fixated stimulus was visible as in the

previous experiment, other stimuli were masked by quadratic Xs with a side length of $.86^\circ$ and a line width of $.18^\circ$. Except for the gaze-contingent manipulation we presented the same sequences as in Experiment 1. All specifications remained unchanged.

Participants were explicitly told to fixate stimuli from left-to-right without skipping single elements. Eye-position was continuously monitored and assigned to the closest symbol. As soon as the eyes moved to another stimulus an X masked the previously fixated stimulus and the fixated stimulus appeared on the screen. Participants scanned the sequence until they had inspected all symbols and responded whether they had found the target by making an eye-movement to the upper/lower right corner of the screen. Response mapping was counterbalanced across participants.

4.7.2.3 Apparatus

The same technical setup was used as in Experiment 1.

4.7.2.4 Data preprocessing

Data preprocessing was the same as in Experiment 1. To ensure that participants acted in accordance with the instruction and in order to reduce noise due to poorly calibrated trials, we excluded trials with regressions, i.e., saccades to previously inspected elements, as well as trials where participant's eyes skipped single elements.

4.8 Supplementary Information

4.8.1 Simulations: Distributions of saccade initiation times

For our simulation studies we use the ICAT model described in the first part of the manuscript. The model consists of two random walks representing the autonomous saccade timer and the temporarily active labile saccade programs. The model approximates fixation duration distributions and can be compared to experimentally observed fixation duration distributions. In a first step, we apply our model to an experiment by Yang and McConkie (2001), which was one of the major motivations for the ICAT architecture. In a second step, we investigate two reading experiments reported by Staub et al. (2010). The experiments showed an early influence of frequency on fixation durations and let the authors conclude that saccades are initiated by lexical processing, i.e., a cognitive trigger. In addition, we compare our model to results from a gaze-contingent manipulation by Reingold et al. (2012). Finally, we investigate the influence of word predictability on saccade timing (Staub, 2011).

The first experiment (Yang & McConkie, 2001) examined local adjustments of fixation durations in a gaze-contingent paradigm. Fixation durations during normal reading were compared with fixations when the page was replaced by (i) a stimulus visually similar to the original text or (ii) a stimulus visually strongly deviating from the original

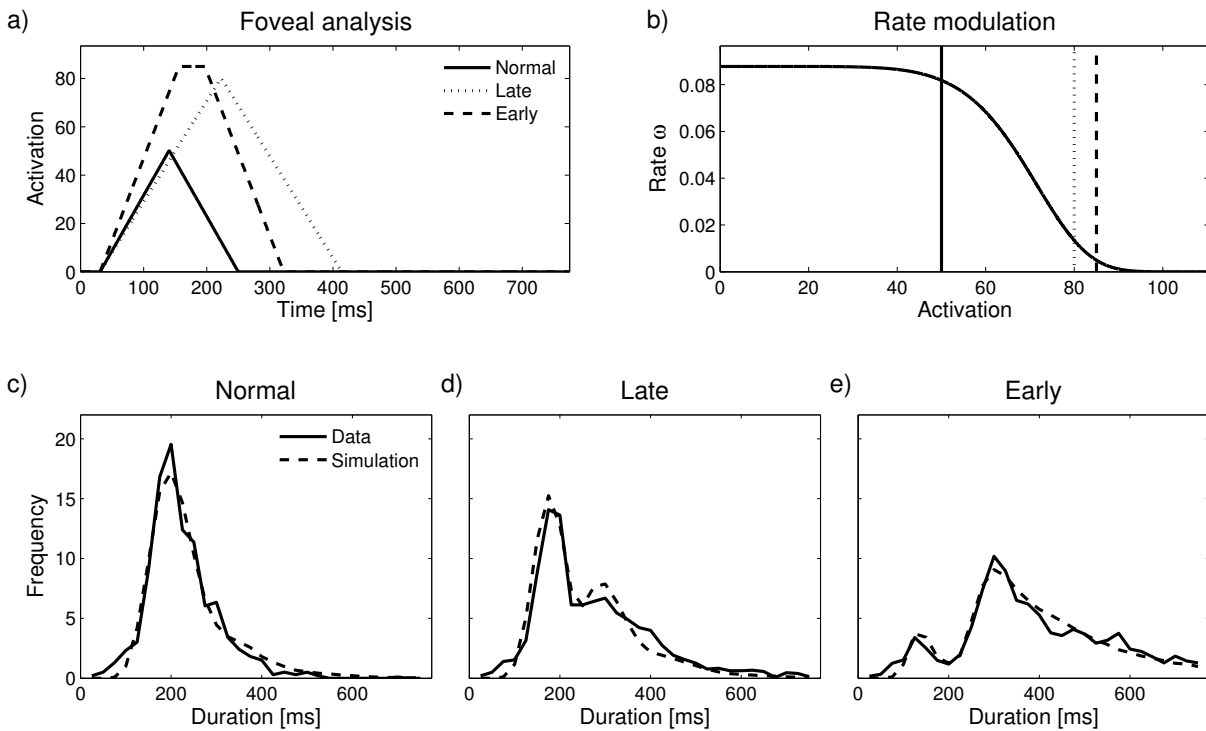


Figure 4.23: Simulation results of Yang and McConkie’s (2001) fixation duration distributions. a) Temporal evolution of activations used in simulations. b) Foveal inhibition. Maximal activations of each condition are marked as vertical lines. Saccade timing is adapted to normal reading. c-e) Simulation results during normal reading, late and early disruptions of the fixation. Experimental data points correspond to fixation durations, simulated data points to saccade initiation times.

text.⁸ Fixation duration distributions during normal reading showed a pronounced peak (Fig. 4.23c). When the stimulus was replaced by a similar stimulus, saccades after long fixation durations (> 275 ms) were executed with a delay (Fig. 4.23d). In contrast, strong visual manipulations disrupted the execution of saccades already shortly after fixation onset (175 – 225 ms) resulting in a bimodal distribution (Fig. 4.23e). In all conditions fixation durations below 150 ms were unaffected by stimulus properties.

For model simulations we used a fixed set of parameters (see Table 4.5) and assumed that experimental conditions differed in terms of processing (Fig. 4.23a). During normal reading activations rise to a moderate level and return soon to zero. When words are replaced by a similar stimulus, activations rise at a similar rate and processing difficulties lead to late increased activations. Only strong visual perturbations affect processing rates immediately and produce early high activations. Rate modulations are shown in (Fig. 4.23b). Saccade timing is adjusted to normal reading (solid line). Transition rates are only weakly modulated by low activations, but are strongly affected by activations exceeding this maximum. Parameters as well as the different time-courses of activations

⁸In the original work Yang and McConkie (2001) tested seven different conditions. We extracted data points from Figure 2 and subsequently averaged across similar conditions. The first distribution contained normal reading only (normal+), the second distribution three conditions with a stimulus visually similar to the original stimulus (normal-, nonword+, X’s+), and the third distribution the remaining conditions (X’s-,dash+,blank-).

Table 4.5: Model parameters for simulation 1–4. Values in parentheses represent parameters modified for simulation of different conditions.

| Parameter | Symbol | Yang & McConkie (2001) | Drieghe (2008) | White (2008) | Staub (2011) | Eq. |
|--------------------------------|--------------|---------------------------|-------------------|-----------------|-----------------|-----------|
| Processing activations | | | | | | |
| Maximum | A_j | 50.0 (80.0/85.0) | 50.0 (65.0) | 50.0 (65.5) | 50.0 | 4.2 & 4.6 |
| Rise | | 0.46 (0.42/0.68) | 0.93 | 0.93 | 0.93 | |
| Plateau | | 0.0 (0.0/40.0) | 0.0 | 0.0 | 0.0 | |
| Onset | | 30.0 | 0.0 | 0.0 | 0.0 | |
| Saccade timer | | | | | | |
| Timer states | N_t | 18 | 18 | 18 | 19 (17/21) | 4.2 |
| Duration ^a | T_j | 205 | 245 | 240 | 195 (212) | 4.2 & 4.7 |
| Foveal inhibition | α | 0.07 | 0.075 | 0.075 | 0.075 | 4.4 |
| | β | 7.0 | 12.0 | 12.0 | 12.0 | 4.4 |
| Saccade programming | | | | | | |
| Oculomotor states | N_o | 20.0 | 20.0 | 20.0 | 20.0 | 4.10 |
| Duration ^a (labile) | τ_{lab} | 150.0 | 150.0 | 135.0 | 125.0 | 4.10 |

^aAll durations are presented in ms.

were chosen by visual inspection of the resulting distributions.⁹ In general, shapes of the experimental and simulated distributions are very similar. Both early and late modulations can be observed with a single set of saccade timing parameters.

Since display changes occurred rarely and were apparent to the reader in the study by Yang and McConkie (2001), the paradigm might be an unusual situation that does not generalize to tasks like normal reading (Rayner, Pollatsek, & Reichle, 2003). Rayner et al. (2011) confirmed this notion by showing that rare and quasi-randomly placed display changes generate more disruption to fixations compared to masking every word. In order to test whether our model accounts for less artificial eye-movement data we used reanalyses of fixation duration distributions (Staub et al., 2010) applied to two reading experiments manipulating word-frequency (Drieghe, Rayner, & Pollatsek, 2008; White, 2008). Word frequency has two major effects on fixation duration distributions. First, low-frequency words shift the entire distribution towards longer durations. Second, low-frequency words affect the skewness of a distribution resulting in a larger frequency effect for long fixation durations.

Model simulations are depicted in Figure 4.24 (upper panels: Drieghe et al., 2008; lower panels: White, 2008). Activations of low-frequency words generate a higher maximum and processing time is prolonged (Fig. 4.24a). The corresponding rate modulations are plotted in Figure 4.24b. The chosen parameter combination (Table 4.5) generates an asymmetric control of fixation durations, since activations below the adjusted difficulty (solid vertical line) do not affect rate while higher activations generate a sharp decline.

⁹In this section we did not use a computational optimization technique since we wanted to qualitatively demonstrate the models viability. Even though we did not aim for the best fit, the quantitative fits are in good agreement with the experimental data.

4. ICAT: Adaptive Control of Fixation Durations

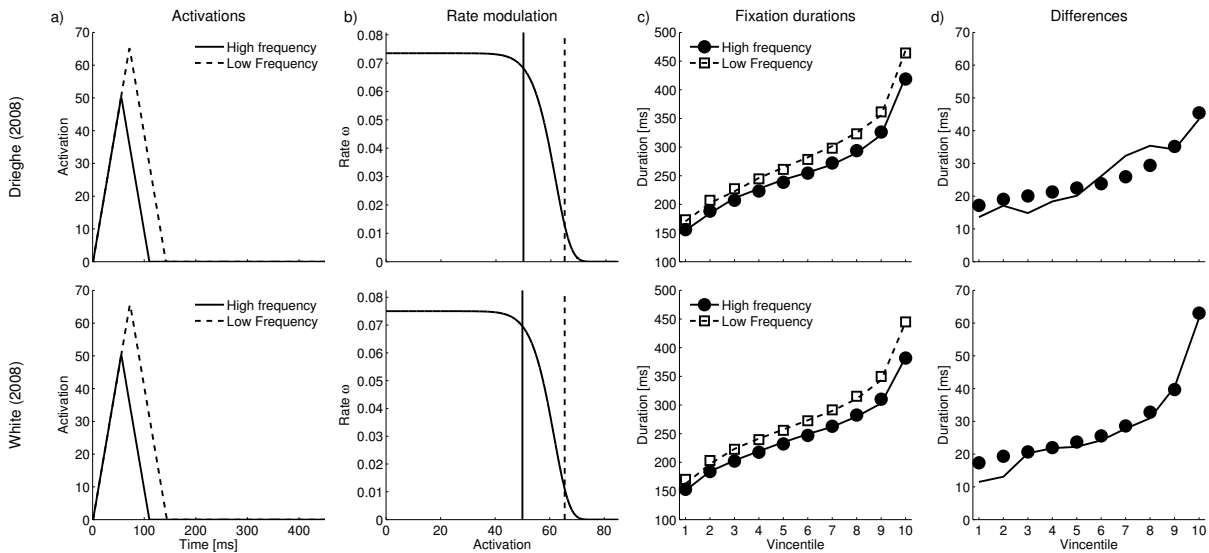


Figure 4.24: Simulation of frequency effects on first-fixation durations (FFD) during reading studied by Drieghe et al. (2008; upper panels) and White (2008; lower panels). a) Temporal evolution of activations for high- and low-frequency words. b) Rate modulation through foveal inhibition. c) Vincentile plots of FFDs. d) Difference in mean FFD between high- and low-frequency words at different Vincentiles. Data taken from Staub et al. (2010).

Resulting Vincentile plots of experimental fixation durations (lines) and simulated data (markers) are in good agreement (Fig. 4.24c). Data points in Vincentile plots correspond to mean fixation durations representing the shortest 10% of fixation durations, the next 10%, and so on. The pure frequency effect, i.e., the difference between mean fixation durations of low- and high-frequency words for each data point, is shown in Fig. 4.24d. Even though saccades are not triggered by lexical processing in our model, the influence of lexical processing on foveal inhibition is sufficient to affect the entire range of fixation durations as well as generating larger frequency effects for longer fixation durations. Reingold et al. (2012) replicated the effects on both shift and skewness. In addition, preventing preview of target words before fixation and thus delaying visual processing of words, reduced the number of fixations affected by frequency from about 90% to about 40%. Furthermore, the shift of the distribution for low-frequency words disappeared, while the skewness remained affected. Following Reingold et al. (2012), we fitted ex-Gaussian distributions to first-fixation durations generated in our simulations. By delaying the temporal evolution of activations by 150 ms, the shift in fitted ex-Gaussian distributions vanished while the skewness remained. Both experiment and simulation showed no effect on the variance parameter.

Finally, we investigated the influence of word predicability on saccade timing within the ICAT model. Using the same analyses as in the previous paragraph, Staub (2011) demonstrated that low predictable words shift the distribution of fixation durations, while leaving skewness and variance of fitted ex-Gaussians unaffected. We assumed that activations for both high and low predictable words remain below the expected difficulty, since expected difficulty should on average be well adapted (vertical line in Fig. 4.25b). Distributions of first-fixation durations as well as the predictability effect are shown for both experiment (lines) and simulations (markers) in Figure 4.25c-d. The model was able to reproduce the observed pattern by assuming different saccade timing parameters prior

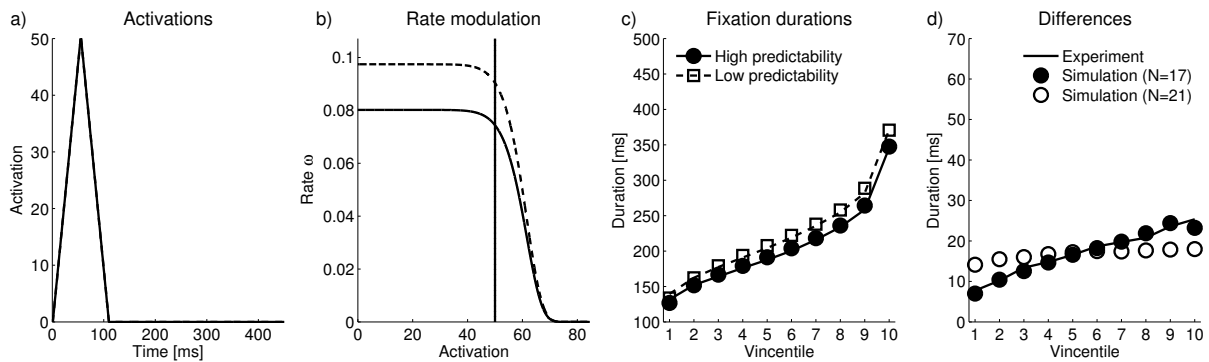


Figure 4.25: Simulation of predictability effects on first-fixation durations (FFD) during reading. a) Temporal evolution of activations for high- and low-predictable words. b) Rate modulation through foveal inhibition. c) Vincentile plots of FFDs. d) Difference in mean FFD between high- and low-predictable words at different Vincentiles. Filled dots correspond to simulations in panel a-c. Open dots show the result of a simulation with no effect on skew. Data taken from Staub et al. (2011).

to fixating a high or low predictable word. Saccade timing was affected by adjusting (i) the expected duration of the next fixation (see Eq. 4.7) and (ii) the number of states N_t , which alters the variance generated by random walks. Even though visual inspection of the experiment suggests a slight effect on skewness, which could be captured by our model (solid line and filled dots in Fig. 4.25d), Reingold et al. (2012) observed no effect in the fitted ex-Gaussian distributions. The visual effect was most likely generated by a few outliers. Therefore, we investigated whether the model is able to generate a pure shift of the distribution. In a second simulation, we kept the estimated parameters and changed only the number of states N_t from 17 to 21. With these parameters a flat line is observed (open circles). The simulations of predictability indicate that saccade timing is affected before fixating the corresponding word. Interestingly, we were not able to reproduce the effect by changing other parameters and keeping saccade timing parameters constant. Hence, predictability (a contextual constraint) has a major influence on saccade timing even before fixating the corresponding word.

In summary, the ICAT model is able to replicate a number of fixation duration distributions in reading and reading-like tasks. Even strong disturbances of fixation duration distributions as generated by rare display changes can be reproduced by our model. Furthermore, the frequency effects and specific modulations of the corresponding distributions are captured by the model. Interestingly, frequency effects have been interpreted as evidence for control by cognitive triggers, since the entire range of fixation durations is affected (Rayner, Liversedge, et al., 2003; Reingold et al., 2010; Staub et al., 2010). We demonstrated that an autonomous saccade timer with inhibitory control is able to generate the observed fixation duration patterns including a stronger frequency effect on long fixations and an effect on skewness but no shift in the distribution when visual input is delayed. Finally, saccade timer adjustments seem to be affected not only by fixation history but also by expectations of upcoming words.

Chapter 5

General summary and conclusions

Eye movements represent an excellent tool to study cognitive processes (Rayner, 2009). However, little is known about the mechanisms that generate sequences of fixations and saccades in paradigms like visual search or scene perception. In particular, the control of fixation durations has been rather neglected across tasks. A notable exception is reading, where both spatial and temporal aspects of eye movement control have been investigated extensively, and with a particular focus on three controversies: (i) the role of oculomotor vs. cognitive control, (ii) serial vs. parallel processing of words, and (iii) the control of fixation durations. By now, several factors have been identified that affect eye guidance during reading, and a number of computational models have been developed that explore the complex dynamics of saccadic sequences.

The present work examined fixation-saccade sequences across tasks. Based on the progress made on eye movement control during reading, we investigated well-established reading phenomena in two non-reading tasks in order to identify general principles of eye movement control. In addition, the investigation of eye movements in non-reading tasks helped to refine our knowledge about eye movement control during reading. Due to the high complexity of eye movements, our approach included the experimental investigation of eye movements in non-reading experiments as well as the evaluation and development of computational models. The upcoming sections discuss the role of oculomotor control, distributed processing, and the control of fixation durations in tasks that require fixation-saccade sequences, before discussing a general computational framework for the control of eye movements.

5.1 Oculomotor control

We investigated four important oculomotor phenomena in two non-reading paradigms (Chapter 2 & 4). As during reading, the fixation position within an object represented a crucial factor that influenced eye guidance. Stimulus elements tended to be fixated at a preferred viewing location (PVL; Rayner, 1979) close to a symbol's center. The variability of fixation positions around the PVL could be described by two processes (McConkie et al., 1988). The saccadic range error (SRE) shifted fixation positions relative to the preceding fixation. Saccades from launch sites closer than a preferred saccade amplitude tended to overshoot the PVL, while saccades from more distant launch sites

led to fixations undershooting the PVL. In addition, sensorimotor noise (cf., perceptuo-oculomotor noise; McConkie et al., 1988) added random deviations around the intended landing site. Two other phenomena were also related to the fixation position within a stimulus. Under most conditions the optimal viewing position (OVP; Vitu et al., 1990), that is, the location where refixation rate is at its minimum, was close to the PVL. However, our experiment revealed an interaction of refixation rate and task demands in Chapter 2, which highlighted the complex dynamics of saccade target selection. Finally, the inverted optimal viewing position (IOVP; Vitu et al., 2001) effect varied somewhat between tasks but fixation durations generally seemed to be longest at the most informative location. Further experiments will need to verify this preliminary observation.

Fixation position effects have now been reported in a number of tasks, including reading and reading-like scanning tasks (for a recent review see Vitu, 2011), as well as the sequential search and visual search tasks presented in Chapter 2 and Chapter 4, respectively. Since these phenomena are not limited to the processing of words, they might constitute basic principles of eye movement control. The existence of a PVL across tasks is probably the least controversial claim. Even in tasks that are ecologically more valid, fixations cluster around specific locations: salient textures during scene perception (Itti & Koch, 2001), task-relevant objects during preparation of sandwiches (Land & Hayhoe, 2001), or task-relevant locations like the tangent point during driving (Land & Lee, 1994). Thus, generally, saccades support actions by directing gaze to task-relevant and informative regions of space. Due to sensorimotor noise, we can expect some variability around these PVLs.

The investigation of other fixation position effects (SRE, OVP, and IOVP), however, represents a serious challenge in many tasks. When using natural scenes, objects are surrounded or even occluded by other objects and the separation of objects from the background is computationally challenging. The position of relevant objects often needs to be determined by hand and, hence, within-object fixation positions are rarely investigated. Nevertheless, Nuthmann and Henderson (2010) analyzed eye movements during scene perception and demonstrated that distributions of fixation positions on objects represent composite distributions. According to their analyses, saccades generally undershot the center of objects. Their estimate of a PVL during scene perception resulted from analyzing all fixations, while ignoring the direction of preceding saccades.

When reported, fixation position effects account for a great amount of variability. The effects are generally attributed to low-level oculomotor control, while higher level cognition only played a minor role (Vitu, 2011). Unfortunately, fixation position effects have only been investigated in a few paradigms. Nevertheless, it is likely that these phenomena can also be observed in other tasks since they guide the eyes to optimally extract visual information. In order to identify factors that contribute to the generation of fixation position effects, we reviewed the tasks that were hitherto investigated (reading, reading like scanning tasks, and the search tasks used in this thesis). An obvious similarity of all paradigms was the use of spatially non-overlapping stimuli presented in front of a plain background. Thus, the identification of objects and object boundaries was straightforward. Furthermore, the size of fixation position effects increased with the gap between objects (a single space between words vs. large gaps between Landolt-'C's). Distributions of fixation positions around the PVL did not overlap for distant objects. For

fixations located in the middle of two symbols, the linear relation of the SRE collapsed, refixation rate was at its maximum (close to 1), and fixation durations were minimal (about 150 ms, which roughly corresponds to the time needed to program a new saccade). But visual gaps are not a prerequisite for fixation position effects. PVL, SRE, OVP, and IVOP are present in scripts where words are not separated by spaces (e.g., Chinese; Yan, Kliegl, Richter, Nuthmann, & Shu, 2010). Paying attention to both spatial arrangement of objects and background will facilitate the observation of fixation position effects across paradigms. Paradoxically, the investigation of seemingly more complicated tasks (e.g., tea making, preparation of food; M. Hayhoe & Ballard, 2005) may contribute significantly to the identification of fixation position effects, since the availability of additional three dimensional cues supports object segmentation.

5.2 Distributed processing

Research on eye movements in reading has been dominated by the question whether words are processed serially or in parallel. While sequential attention shift (SAS) models assume that processing is always limited to a single word, parallel gradient (PG) models propose distributed processing across several words. In addition to reading, E-Z Reader, a fully implemented computational SAS model, has recently also been used to simulate eye movements in a set of scanning tasks (Reichle et al., 2012). In Chapter 3, we investigated three predictions of SAS models in a scanning task that encouraged serial processing of stimulus elements: (i) the absence of parafoveal-on-foveal (PoF) effects, (ii) the absence of long-range modulations on target selection, and (iii) the presence of skippings costs. First, fixation duration modulations through processing of upcoming stimulus elements (i.e., PoF effects) contradict SAS models, since the decision to move the eyes is made before attention shifts to a parafoveal stimulus. Contrary to this, we observed a PoF effect of the upcoming stimulus_{n+1} that prolonged fixation durations on stimulus_n in the sequential search task (see also Chapter 4). Most critically, the prolongation was also observed before refixations, which represents a conservative test of PoF effects that excludes a possible role of mislocated fixations. Second, long-range modulations revealed that distant stimuli affect the proportion of refixations, forward saccades, and skippings. Since these stimuli were far away (up to five stimulus elements) from the next saccade target (the restricted locus of attention in SAS models), our findings are incompatible with the assumption of serial object processing. Third, skipping of stimulus elements prolongs fixation durations in SAS models, since a saccade towards the skipped symbol needs to be canceled and replaced by a new saccade. Contrary to prolonged fixation durations, we observed shorter fixation durations before skipping saccades. Follow-up analyses excluded priming and path statistics as possible causes for the observed skipping benefits. Thus, even though SAS models might represent an approximation of eye movement control (Reichle et al., 2012), our analyses reveal that SAS models are too limited to capture the full complexity of eye guidance. Since all predictions of SAS models were rejected in our scanning/search task, we concluded that sequential attention shifts are not the basis of eye movement control. Instead, our results emphasize the important role of distributed processing during scanning.

Our results resemble eye movement control in a few other related tasks. In particular, PoF effects and skipping benefits have been reported during normal reading (PoF: e.g., Kliegl et al., 2006; skipping benefits: e.g., Kliegl & Engbert, 2005), reading of shuffled text (PoF & skipping benefits: Schad & Engbert, 2012), and while searching word lists (PoF: Kennedy et al., 2002). Across tasks, our eyes seem to be controlled by distributed processing. Rarely, if ever, do the visual and oculomotor systems switch to a purely serial processing mode. Even during sequential search (Chapter 3), where the task required to establish a serial order of symbols, the oculomotor system relied on distributed processing.

One observation about distributed processing deserves further consideration. We found a clear dissociation between the control of fixation durations and target selection. While fixation durations were only affected by the fixated (foveal) and the next (parafoveal) symbol, the six upcoming stimulus elements modulated target selection. A similar dissociation has also been reported for the perceptual span during reading (Rayner et al., 1981). Thus, the decisions when and where to move the eyes were (at least partially) independent during reading and sequential search (cf., Findlay & Walker, 1999). This dissociation represents a major challenge for SAS models, where both decisions are generated by the same process.

In contrast, current PG models assume partial independence of target selection and control of fixation durations and seem, in principle, compatible with the results observed during sequential search. Nevertheless, it is not obvious how a computational model based on distributed processing generates PoF effects, long range modulations, and skipping benefits. In its current form, SWIFT (Engbert et al., 2005) does not possess explicit mechanisms to generate any of these effects. Recent model simulations, however, successfully replicated skipping benefits during reading (Engbert & Kliegl, 2011), reading shuffled text (Schad & Engbert, 2012), and a scanning task (Chapter 4). The simulated skipping benefits result from a targeting bias towards rudimentary processed objects in SWIFT. In contrast, PoF effects and long range modulations are currently not well captured by model simulations and represent serious benchmarks for all models of eye movement control.

5.3 Control of fixation durations

In the first part of Chapter 4, we reviewed the literature on fixation duration control in saccadic sequences during reading, visual search, and scene perception. Across tasks, fixation durations can be described by asymmetric control. An increase in processing demands prolongs fixation durations immediately, while a decrease in processing demands reduces fixation durations with a temporal delay. We proposed that the asymmetries in fixation durations originate from two different levels of control: (i) *local control* depends on processing of the foveal item and affects the current fixation while (ii) *global control* is related to overall task requirements and affects fixations over longer periods (not just the current fixation). Cognitive trigger theories and mixed control models provide detailed explanations of local control. Global control, however, is either neglected or only

implicitly assumed in current theories, even though it constitutes a key mechanism of indirect control (Hooge & Erkelens, 1998).

Based on our conclusions, we developed a computational model for the control of fixation durations: ICAT. Our model consists of three core principles. First, an autonomous timer initiates new saccade programs after random time intervals, independent of ongoing processing. Second, foveal inhibition delays the initiation of a saccade program when foveal processing is highly demanding. As a consequence, fixation durations can be prolonged immediately. Third, both the average durations of autonomous saccade timing and the strength of foveal inhibition adapt over time and depend on expected foveal processing demands. These expectations, in turn, rely on the preceding fixation history. The interaction of these principles leads to an asymmetric control of fixation durations with immediate prolongations when processing demands increase (local control) and a temporal delayed decline when processing demands decrease (global control). In model simulations we examined the interplay of global and local control mechanisms. ICAT is the first computational model that implements adjustments of saccade timing explicitly. Our simulations revealed the importance of global control for asymmetric control of fixation durations and provide a promising starting point for the temporal control of eye movements and future investigations of fixation durations and the temporal control of eye movements.

The control of fixation durations depends on foveal and parafoveal processing during many tasks, including reading (e.g., Kliegl et al., 2006), scene perception (Diepen & d'Ydewalle, 2003), and visual search (Hooge et al., 2007). The impact of parafoveal processing, however, was rather modest when compared to the influences of foveal processing. Interestingly, processing of foveal stimuli has been assumed to directly affect saccade timing, either in the form of a cognitive trigger (e.g. E-Z Reader, Reichle et al., 2012), or via modulations of saccade initiation (like foveal inhibition in ICAT; cf., Engbert et al., 2005). Thus, in most models, foveal processing influences strongly the decision when to move the eyes. In contrast, the mechanisms that generate PoF effects do not necessarily result from modulations of saccade initiation. In SWIFT (Engbert et al., 2005), fixation duration modulations by the next word evolve from the dynamics of target selection and can be observed in selected subsets of fixations (e.g., single fixation durations). Furthermore, the time needed to program a saccade depends on the size of the intended saccade amplitude. On average, small saccades lead to slightly longer fixation durations. Thus, PoF effects in SWIFT are either caused by target selection effects or by temporal differences during the preparation of saccades. Both mechanisms, however, do not affect the decision when to move the eyes. Whether these mechanisms suffice to account for PoF effects across tasks needs to be investigated in future research. As an alternative, processing within the fovea and parafovea may directly modulate saccade timing. Similar to foveal inhibition, parafoveal inhibition may monitor processing in both the fovea and the parafovea and delay the initiation of the next saccade correspondingly.

As a final remark, our simulations revealed the crucial role of saccade preparation for the generation of long fixation durations. According to Becker and Jürgens (1979), labile saccade programs can be canceled and replaced by the initiation of a new saccade program. Since this process may be iterative, several saccade programs may be canceled in succession, which leads to the generation of long fixation durations. Even though the

control principles of ICAT account well for mean fixation durations as well as for a large fraction of fixation duration variability, the long tail of fixation duration distributions could only be captured in our simulations when we allowed for the cancellation of labile saccade programs.

5.4 Computational models

In the second part of Chapter 4 we evaluated our insights about oculomotor control, distributed processing, and fixation duration control in a computational model that considered both spatial and temporal aspects of eye guidance. The assumptions about saccade timing proposed in ICAT were incorporated into an existing model of eye-movement control during reading (i.e., SWIFT, Engbert et al., 2005) and subsequently evaluated in two versions of a search task. Model simulations exhibited realistic spatio-temporal control of eye movements. The full model accounted for average fixation durations, fixation duration distributions, different saccade types, and oculomotor control related to fixation positions within a stimulus element. Due to the interaction of saccade targeting and fixation duration control, our model even generated skipping benefits, which has generally been interpreted as evidence for distributed processing (Engbert & Kliegl, 2011).

Our model consists of three main components related to the controversies of eye movement control. First, saccades are initiated by an autonomous timer that can be delayed by foveal inhibition, when processing is highly demanding. Due to a global control mechanism both random timing and foveal inhibition continuously adapt over time. In Chapter 4 we demonstrated that the interaction of these principles leads to asymmetric control, which is in agreement with our current understanding of fixation durations during reading, visual search, and scene perception. Second, distributed processing provides access to several objects simultaneously. While peripheral processing primarily affects target selection, foveal (and parafoveal) processing also controls fixation durations. In our model, a temporally evolving activation field realized distributed processing and served as a saliency map for target selection (Erlhagen & Schöner, 2002). Evidence for distributed processing has been reported in several tasks, including reading (e.g., Kliegl et al., 2006), reading shuffled text (Schad et al., 2010), and scanning tasks (Chapter 3 & 4). Third, low level oculomotor control leads to systematic effects of the relative fixation position within an object. According to our model, saccades generally target at a preferred viewing location within an object (PVL; Rayner, 1979). The exact fixation position is a function of the preceding launch site and random sensorimotor noise (cf., McConkie et al., 1988). Large saccadic deviations, however, lead to immediate initiations of new saccade programs (mislocated fixations; Nuthmann et al., 2005). Mislocated fixations contribute to systematic modulations of refixation rate (OVP; Vitu et al., 1990) and fixation durations (IOVP; Vitu et al., 2001). All oculomotor phenomena covered by the extended version of ICAT, have been observed in a number of tasks (reading: Rayner, 2009; mindless reading: Vitu et al., 1995; scanning tasks: Chapters 2 & 4).

The similarity of eye movement patterns in tasks like reading, scanning, and visual search led to the conclusion that a set of control principles governs eye movements across

tasks. Although our computational model was developed for reading and scanning tasks, the proposed framework can, in principle, be adapted to any task that requires sequences of fixations. In its current form the model operates at the level of objects. While the activation field can easily be transformed from a discrete set of objects to a spatially continuous map (like a saliency map during scene perception; Itti & Koch, 2001), the role of objects for the generation of fixation position effects needs to be clarified. Nonetheless, the simulations presented here as well as simulations of related models demonstrated the compatibility of our framework with eye movement control during reading (Engbert et al., 2005), reading shuffled text (Schad & Engbert, 2012), and search tasks (see preceding chapters). Since model generalizability is a key concept of model evaluation (Pitt et al., 2002), the proposed control principles likely provide elementary concepts of eye guidance. Further research will need to verify the generalizability of our assumptions and explore the potential compatibility with more natural tasks (e.g., M. Hayhoe & Ballard, 2005).

5.5 Conclusions

The present thesis investigated a great number of phenomena of eye movement control in two non-reading scanning tasks. In general, eye guidance resembled eye movement control during reading. Low level oculomotor control generated effects of the fixation position within an object, distributed processing affected both target selection and saccade timing, and fixation durations could be described by asymmetric control. Based on the similarities of eye movement control in a number of paradigms we conclude that a general set of control principles governs eye movement control across many (if not all) tasks that require sequences of fixations and saccades. Due to the complex dynamics of eye movement control, our experimental approach was supported by the development and evaluation of computational models. The first model, ICAT, focussed on the control of fixation durations. Most importantly, ICAT is the first computational model with a global control mechanism that continuously adjusts saccade timing. This mechanism represents the basis of asymmetric control. In a second model, we incorporated ICAT into a full model of eye movement control (i.e., SWIFT; Engbert et al., 2005) in order to evaluate the interplay of spatial and temporal control. The principles of our second model are generally compatible with eye movement control in tasks that require fixation-saccade strategies and provide a promising starting point for the investigation of saccadic sequences in visual search and scene perception.

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