Oculomotor control in a sequential search task

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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.
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1. Introduction

The analysis of eye movements is among the best measures of visual information processing in visual search, reading, or general scene perception (Findlay & Gilchrist, 2003; Rayner, 1998). First, eye movements provide an online measure of processing, because of the fast sampling rate of about 3–5 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; 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; Hoffmann & Subramaniam, 1995; Kowler, Anderson, Dosher, & Blaser, 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, Longtin, & Kliegl, 2002; Engbert, Nuthmann, Richter, & Kliegl, 2005). Interestingly, using a theoretical model, we

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

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. McConkie, Kerr, Reddix, & Zola, 1988; Nuthmann, Engbert, & Kliegl, 2005; Rayner, 1979; Vitu, O'Regan, & Mittau, 1990; Vitu, McConkie, Kerr, & O'Regan, 2001). 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.

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 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 (Hooge & Erkelens, 1996, 1998, 1999; Luria & Strauss, 1975; Motter & Belky, 1998a, 1998b; Williams, 1967; 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 (Findlay, 1997; Luria & Strauss, 1975; Motter & Belky, 1998b; Williams, 1967; Zelinsky, 1996), 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; Parkhurst & Niebur, 2003; Reinagel & Zador, 1999; 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 (Hayhoe & Ballard, 2005). Instead, saccades aim at interesting or informative regions in a scene (Buswell, 1935; Loftus & Mackworth, 1978; Yarbus, 1967) 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]

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. 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 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).

The variability of within-word fixation position is a driving force of two other effects observed in reading. First, McConkie, Kerr, Reddix, Zola, and Jacobs (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. 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. 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 Engbert, Nuthmann, & Kliegl, 2007; Nuthmann, Engbert, & Kliegl, 2007).

1.3. Oculomotor control in other tasks

Oculomotor effects were studied in few tasks other than reading and visual search. First, Vitu, O'Regan, Inhoff, and Topolski (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 at 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

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[2] In 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, Nuthmann, & Engbert, 2006; see Reichle, Rayner, & Pollatsek, 2003, for a discussion of alternative views).
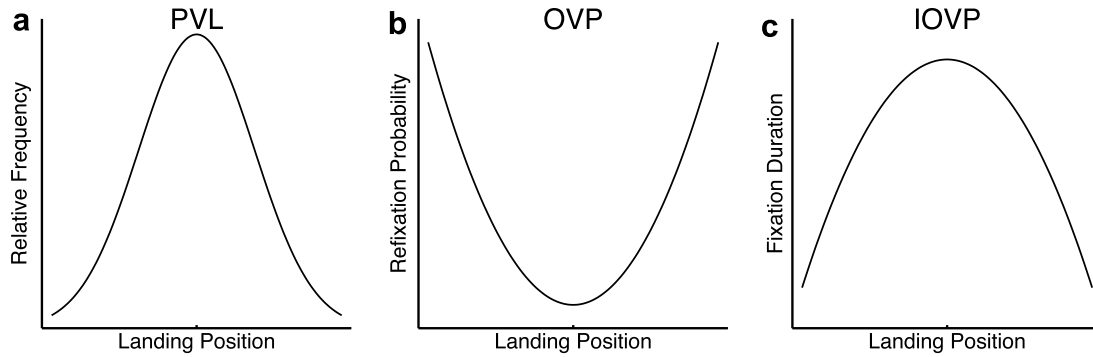
Fig. 1. Schematic illustration of basic oculomotor phenomena in reading. (a) The preferred viewing location (PVL) is the local maximum of the distribution of within-word fixation positions. (b) The optimal viewing position (OVP) can be read off from the minimum of the probability of generating a refixation. (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.

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.

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 Hooge 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. Methods

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. 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. Fig. 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
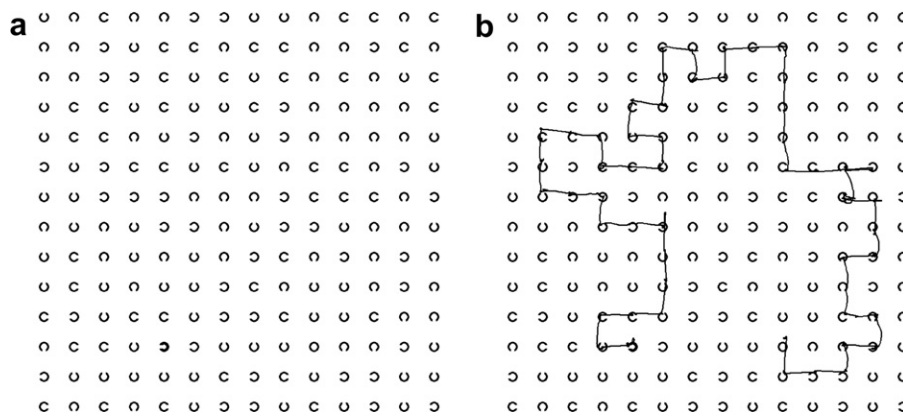

Fig. 2. Sequential search task. (a) Participants were instructed to follow a path given by a sequence of Landolt 'C's, where the opening of each stimulus element in a sequence gives the movement direction to the next symbol. The starting symbol is marked with bold font, while the target symbol is a closed circle. (b) A typical eye-movement trajectory generated by a participant.

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.

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 movements 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.

2.4. 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.

3. Results

An example of a participant's eye movements during the sequential search task is shown in Fig. 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 Section 2). 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 Fig. 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 Fig. 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. 3c) and oblique skippings (Fig. 3d). Skippings are frequently followed by a regression, which is illustrated in Fig. 3d. In addition, participants produced saccades to symbols outside the required movement path (Fig. 3e), which we defined as saccadic errors.

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 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.

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
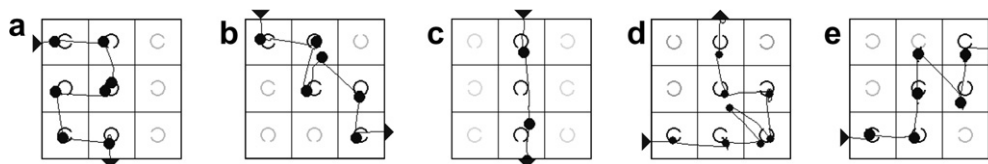

Fig. 3. Classification of saccades and fixations. Straight horizontal and vertical lines around a symbol indicate the boundaries which we used to map fixation positions to symbols. For clarity, symbols on the path are highlighted in bold font. Arrow heads indicate the movement direction. (a) Forward 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.

Table 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

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 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 (Kliegl et al., 2006; Rayner, 1998), 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.

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. 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.

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

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.,
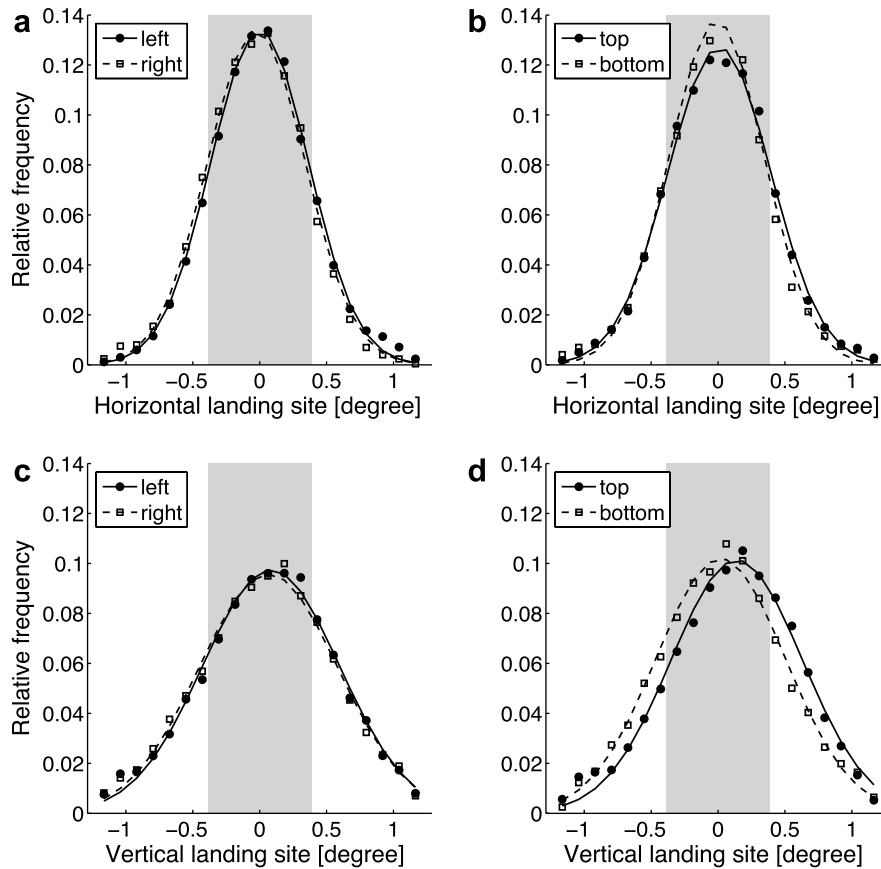
Fig. 4. Preferred viewing locations within fixated symbols. (Top panels) Distributions of the horizontal component of landing positions for symbols (a) with horizontal gap positions and (b) with vertical gap positions. (Bottom panels) Corresponding distributions of the vertical component of landing positions 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.

Table 2
Within-symbol fixation position: preferred viewing location

Gap position	Horizontal component (°)		Vertical component (°)	
	Mean	SD	Mean	SD
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

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.

Figs. 5 and 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 (Figs. 5a and b and 6c and 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
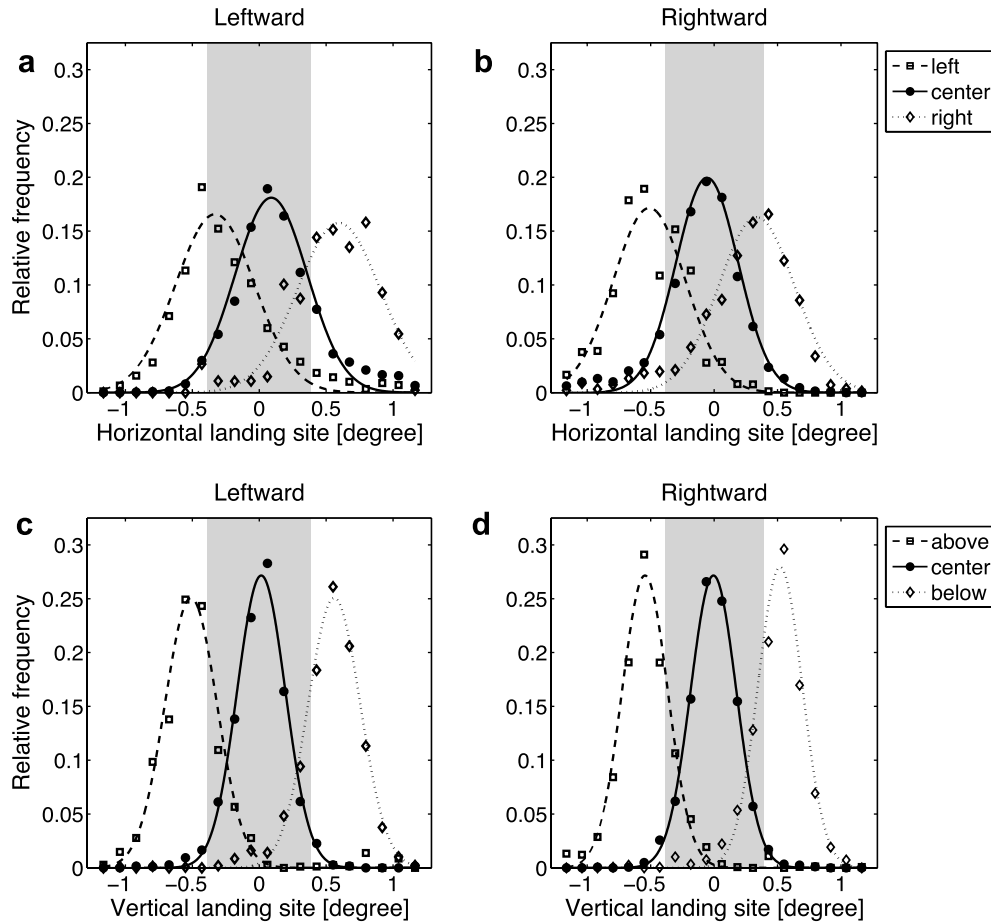
Fig. 5. Launch site effect for saccades to the right and left. (a and b) Horizontal landing site distributions for launch sites to the left of, at the center, or to the right of a symbol. (c and d) Vertical landing sites after saccades launched above, below or the center of a symbol. Landing site distributions 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.

8 cases plotted in Figs. 5 and 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 of the eye-movement path given by the task. From McConkie et al. (1988) work, we expected linear relations between the components of v_x, v_y and w_x, w_y, i.e.,

$$w_{xi} = \alpha_{xi} + \beta_{xi} v_{xi}, \tag{1}$$
$$w_{yi} = \alpha_{yi} + \beta_{yi} v_{yi}, \tag{2}$$

where i denotes the direction of the saccade vector.[3] The estimated parameters give insight into the relation between launch site and landing site, where α displays the mean 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. 7), between about $-0.6°$ and $+0.6°$. 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

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[3] Note, 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.
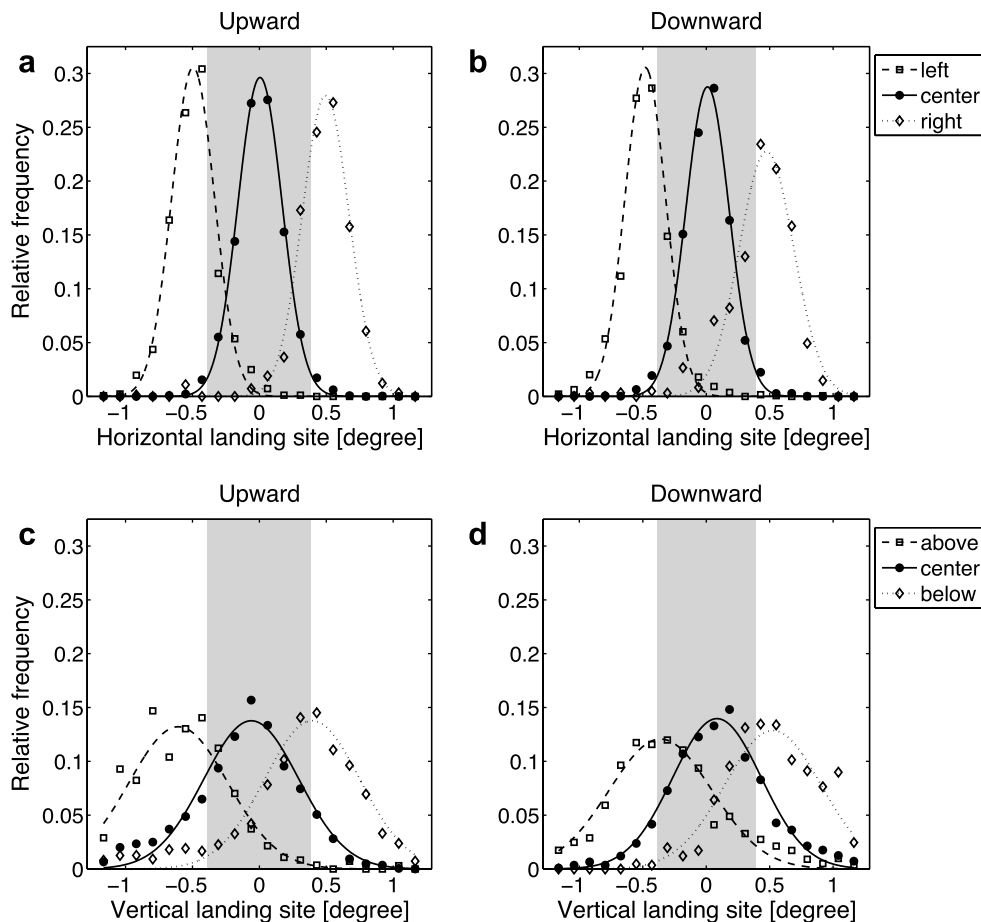
Fig. 6. Launch site effect for upward and downward saccades. (a and b) Horizontal landing site distributions for launch sites to the left of, at the center, or to the right of a symbol. (c and d) Vertical landing sites after saccades launched above, below or the center of a symbol. Landing site distributions were calculated separately for the two possible saccade directions (left panels, upward saccades; right panels, downward saccades).

slopes β) are given in Table 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.

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.
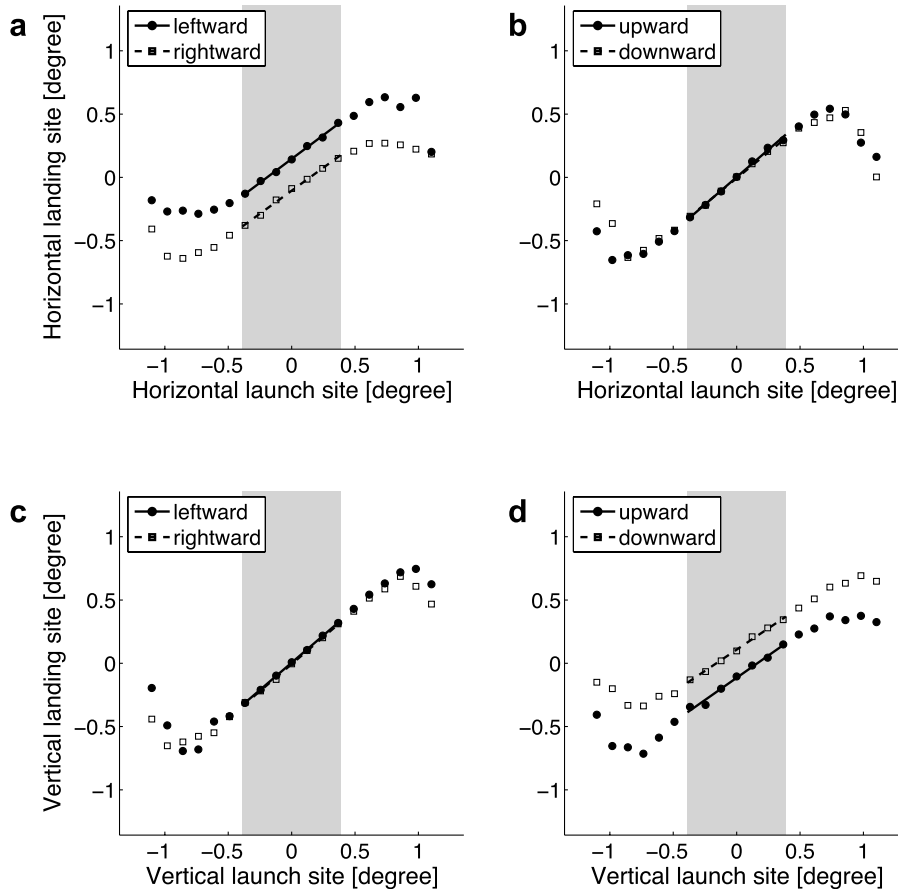
Fig. 7. Numerical calculation of the saccadic range error. Mean landing sites as a function of launch site split by (a and b) horizontal launch site component and (c and d) vertical launch site component. Saccadic range errors were calculated separately for horizontal (left panels) and vertical saccade vectors (right panels).

Table 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

Our results extend the findings of Vergilino-Perez and 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.

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. 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. 8b and 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
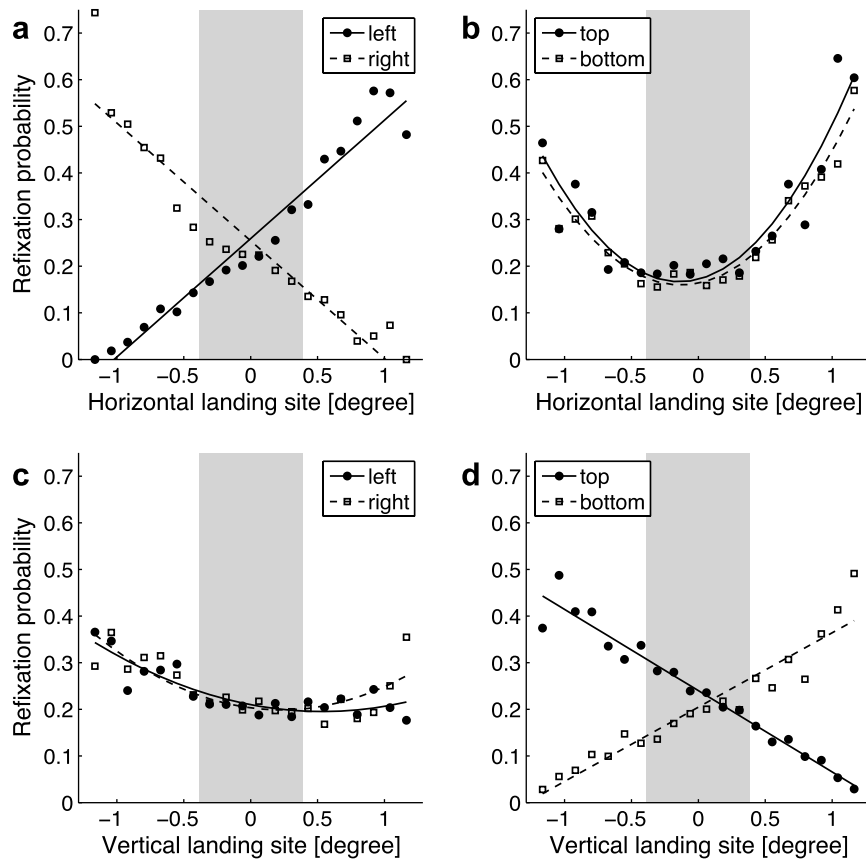
Fig. 8. Refixation probabilities as a function of landing position. (a and d) For gap orientations parallel to the component of the landing position considered, a linear decrease towards the gap position within the symbol is found. (b and c) For gap orientations perpendicular to the component of the 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.

observed, where the probability decreases towards the gap position (Fig. 8a and 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,

$$p(x) = A_0 + B_0(x - C_0)^2, \tag{3}$$

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 to noisy. Therefore, we employed a bootstrap method to determine reliability of the OVP curves. Efron and Tibshirani (1993) proposed an algorithm to estimate standard errors in this type of data reliably. One thousand 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 the mean. Table 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 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]

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 (Nuthmann et al., 2005, 2007; Vitu et al., 1990), 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.

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

Table 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

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 Fig. 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),

$$f(x) = A_1 + B_1(x - C_1)^2. \tag{4}$$

Separate analyses were performed for horizontal vs. vertical landing positions and for different gap orientations. In Eq. (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 5. Bootstrap samples were computed as described in the previous section.

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 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

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[4] Additionally, 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.

[5] The 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).
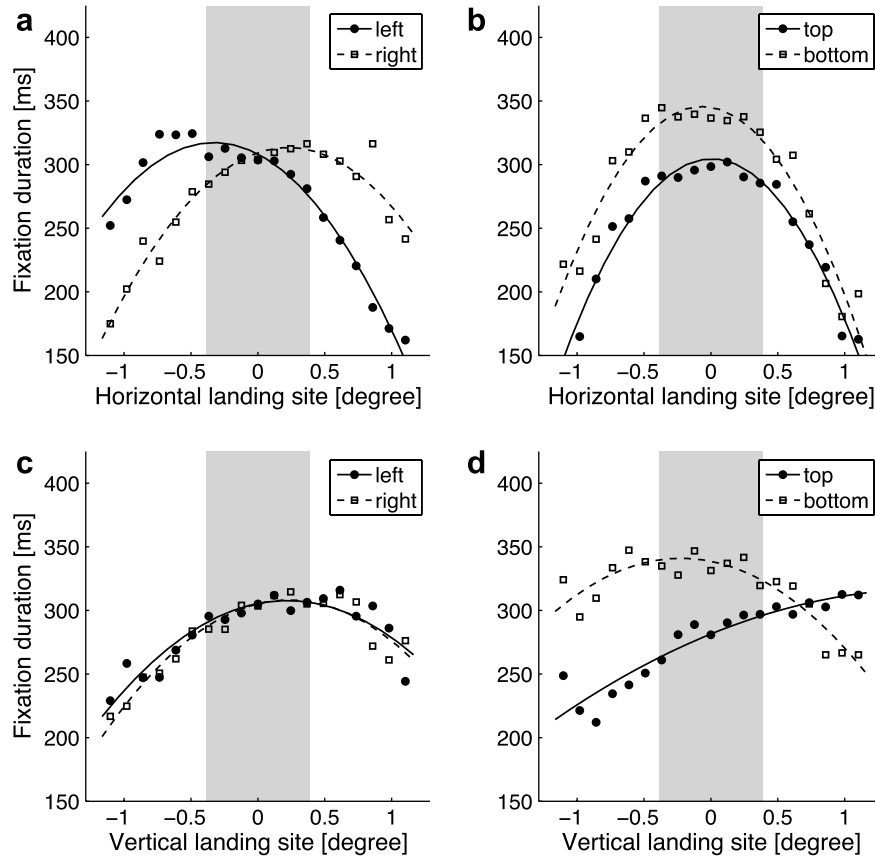
Fig. 9. The inverted optimal viewing position effect for all first fixations. (a and b) Mean fixation durations at different horizontal landing positions show a pronounced inverted U-shape. Lines represent estimated quadratic curves of fixations on symbols with horizontal vs. vertical gap orientation. (c and 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.

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

Table 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 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.

4. Discussion

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 the 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.

4.2. Implications for eye-movement control

Most research on the influence of relative fixation position on eye movements was confined to reading (Hyönä, 1995; McConkie et al., 1988, 1989; Nuthmann et al., 2005; Rayner, 1979; Vitu et al., 1990, 2001; White & Liversedge, 2006) or mindless reading (Nuthmann et al., 2007; Rayner & Fischer, 1996; Vitu et al., 1995). 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 effect 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, Engbert, and Kliegl (2005; see also Nuthmann et al., 2007; Engbert 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

where 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. Predicitions of this complex behavior, however, might only be derived from computational models of eye-movement control.

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, Carpenter, and Shillcock (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 (Engbert et al., 2007; Nuthmann et al., 2005, 2007). Broad distributions of within-word landing positions indicate that some saccades might be misguided and land on an adjacent 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).

5. 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.

Acknowledgments

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