ARTICLE IN PRESS

BRES-38513; No. of pages: 10; 4C:

BRAIN RESEARCH XX (2008) XXX–XXX

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Research Report

On the specificities of the inverted-optimal viewing position effect and their implications on models of eye movement control during reading

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ARTICLE INFO

Article history:
Accepted 23 August 2008

Keywords:
First-fixation duration
Saccade programming
Visual word recognition
Reading
Optimal viewingposition
OVP
Inverted-optimal viewing position
I-OVP

ABSTRACT

During reading, the probability of refixations increases and the duration of first fixations decreases with growing distance of the initial fixation position from a word's center (i.e., the optimal viewing position, OVP). The question, whether or not refixation-OVP and first-fixation duration inverted-OVP curves are modulated by the lexical characteristics of the actually fixated stimulus is still a matter of debate. The aim of the present study is to investigate the relative temporal succession of the availability of lexical information and the preparation of saccadic motor programs. For that purpose, the lexicality effect in event-related brain potentials and the onset of saccadic eye movements (as an observable indicator for the preparation of saccadic motor programs) were recorded simultaneously. Initial fixation position on a stimulus was experimentally varied by means of the *variable viewing position paradigm*. The observed first-fixation duration inverted-OVP curve was not modulated by lexical characteristics and an effect of initial fixation position on the onset of the lexicality effect in event-related brain potentials (i.e., a lexicality-OVP effect) could be observed. An analysis of the time-course of both effects revealed that it is highly unlikely that refixations as observed by the *variable viewing position paradigm* can be modulated by lexical characteristics. An interpretation in terms of an early cohort of refixations that corrects for suboptimal initial fixation positions and that is not influenced by lexical characteristics of the stimulus material is favored. Subsequently, it is analyzed how current models of eye movement control can account for the present study's results.

1. Introduction

The so called optimal viewing position (OVP) effect describes the observation that word recognition performance is superior when a word is initially fixated slightly left to its center and gets worse with increasing distance of the initial fixation to this position. This effect is supposed to be caused by a drop-off in visual acuity with increasing retinal eccentricity. If the initial fixation position deviates from the optimal viewing position, responses are slower and more error prone during lexical decision (e.g., Nazir et al., 1991; O'Regan and Jacobs, 1992) and articulation latencies increase during naming (O'Regan and Jacobs, 1992; O'Regan et al., 1984). Initial fixation position is furthermore reported to affect eye movements: If a word is initially fixated near its center, refixation probability is lowest and gaze duration is shortest; with increasing distance

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doi:10.1016/j.brainres.2008.08.065

to the OVP, refixation probability is greater (refixation–OVP effect) and gaze durations are prolonged (O'Regan et al., 1984). The refixation–OVP effect is documented for both, the recognition of words presented in isolation (Vitu et al., 2007; Vitu et al., 1990) and for the continuous reading of text (McConkie et al., 1989; Rayner et al., 1996; Vitu et al., 2001). Whereas there is wide agreement concerning the *existence* of a refixation–OVP effect, the evidence regarding the issue whether or not the refixation–OVP effect is modulated[1] by word characteristics such as word-frequency is inconsistent. For the recognition of words presented in isolation, no influence of word-frequency on the refixation–OVP curve is reported (Vitu et al., 2007; Vitu et al., 1990). This finding stands in contrast to evidence from studies suggesting that refixation probability is modulated by word-frequency (for a detailed discussion see, e.g., Pollatsek and Rayner, 1990, p. 153).

Apart from its effect on refixation probability, initial fixation position was also shown to affect first-fixation duration — however, in a counterintuitive way. If a word is fixated twice, the duration of the first fixation is *longest* if its initial position is near the word's center; with increasing distance to the optimal viewing position, first-fixation durations get *shorter*. This effect was initially reported by O'Regan et al. (1986) and O'Regan and Lévy-Schoen (1987) and was systematically investigated by Vitu et al. (2001) and termed the *inverted-optimal viewing position* (I-OVP) effect. Again, the first-fixation duration I-OVP effect is documented for the recognition of words presented in isolation (O'Regan et al., 1986; O'Regan and Lévy-Schoen, 1987; Vitu et al., 2007) as well as for the continuous reading of text (Vitu et al., 2001). The I-OVP effect is at odds with several findings from the literature. First of all (as discussed in detail by Vitu et al., 2001) words are supposed to be indentified most easily if they are fixated near their center. First-fixation durations (that in general are shorter when processing is easier) should therefore be shortest if a word is fixated close to its center — not longest, as characterized by the I-OVP effect. Second, the first-fixation duration I-OVP curve is reported not to be modulated by word characteristics such as word-frequency (cf., Vitu et al., 2007), a finding that is at odds with evidence showing that the duration of the first fixation is affected by word-frequency (e.g., Inhoff, 1984; Rayner et al., 1996).

1.1. *Aim of the present study*

As outlined above, the specifics of both, the refixation-OVP and the first-fixation duration I-OVP effect are in conflict with findings from the literature. Of central importance is the issue whether or not the duration of the initial fixation on a word and the location of its succeeding fixation are modulated by lexical characteristics of the stimulus material such as word-frequency. A specific bit of information can only influence the duration of the first fixation and the location of the second fixation if it is available prior to a certain deadline: The last point in time at which the motor program of a saccade can still be modified is estimated to be around 50 ms prior to the onset of the respective saccade (Sereno and Rayner, 2003; Sereno et al., 1998). The issue whether or not the refixation-OVP and the first-fixation duration I-OVP effect are affected by lexical characteristics such as word-frequency therefore is related to the question of the relative temporal succession of the availability of lexical information on the one hand, and the preparation of a saccadic motor program (with the onset of a saccade as an observable indicator) on the other hand.

The start of a cognitive process can be estimated with high temporal resolution by determining the onset of its electrophysiological correlate as reflected by brain potentials. In the present study, the differentiation of brain potentials in response to words and pseudowords (i.e., the lexicality effect) provides a potential marker for lexical access. The onset of saccadic eye movements is determined by means of the electro-oculogram (EOG) which is registered during the course of electroencephalographic recording. To examine effects of initial fixation position, a lexical decision task is used in combination with the *variable viewing position paradigm* (O'Regan et al., 1984): In order to impose a specific initial fixation position during the recognition of an item, a fixation marker is presented in the center of the screen that is replaced by the stimulus, the horizontal position of which is varied systematically. For example, in order to impose an initial fixation position on the fifth letter of a word, the horizontal position of the experimental stimulus is adjusted in a way that its fifth letter is exactly in the position of the preceding fixation marker.

The present study's approach allows to simultaneously assess speed and accuracy of responses, the onset of saccadic eye movements and the point in time of the onset of lexical access within a single setting, thereby taking advantage of the combined recording of eye movements and brain potentials (Sereno and Rayner, 2003) in order to establish a timeline of the aforementioned processes.

2. Results

2.1. *Behavioral data*

Percentage of errors and response times were submitted to separate 2×5 repeated measures ANOVAs with lexicality (words vs. pseudowords) and initial fixation position (1st to 5th letter) as within-subject factors. Where appropriate, *df*s were adjusted using Greenhouse–Geisser correction for the violation of sphericity. In case of a reliable main effect of initial fixation position, pair-wise comparisons were performed as post-hoc tests for reliable differences between adjacent positions, i.e., between the 1st and the 2nd, the 2nd and the 3rd position and so forth.

2.1.1. *Error OVP effect*

The percentage of errors was higher for words than for pseudowords, as indicated by a main effect of lexicality, $F(1,17)=56.71$; $MSE=.01$; $p<.001$. It was also dependent on initial fixation position, as revealed by the corresponding main effect, $F(3.38,57.53)=20.08$; $MSE=.003$; $p<.001$; the magnitude of the initial fixation position effect was slightly modulated by

[1] By *modulation* we intend to refer to any kind of influence of word characteristics on OVP and I-OVP curves, main effects of lexicality (i.e., a vertical shift of the curve), as well as an interaction between lexicality and fixation position (i.e., different shapes of the curves).

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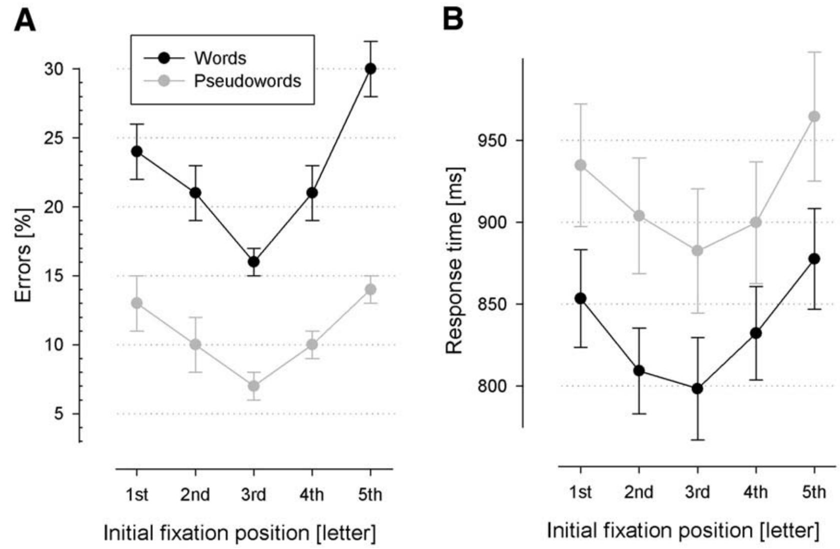

Fig. 1 – Mean percentage of errors (A) and mean response times (B), plotted for words (black) and pseudowords (grey), separately for all five initial fixation positions (bars indicate standard error of the mean).

the lexical status of the stimulus, as indicated by an initial fixation position by lexicality interaction of borderline reliability, $F(3.13,53.16)=2.67$; $MSE=.003$; $p=.054$. As obvious from Fig. 1(A), the percentage of errors for both, words and pseudowords, was smallest if a stimulus was initially fixated on the 3rd letter; the percentage of errors increased with increasing distance of the initial fixation position from the word center. For words, post-hoc tests revealed reliable differences between all adjacent initial fixation positions, all $ps \leq .05$. For pseudowords, reliable differences were found between all adjacent initial fixation positions, all $ps<.025$, except between the 1st and 2nd position, $p=.10$.

2.1.2. Response times OVP effect

Incorrect responses and responses greater than 3000 ms (.07%) were excluded from analysis. As evident from Fig. 1(B), response times were shorter for words than for pseudowords, as indicated by a main effect of lexicality, $F(1,17)=13.36$; $MSE=23{,}172$; $p<.01$. Initial fixation position affected response times, as indicated by a main effect, $F(2.12,36.04)=11.98$; $MSE=5812$; $p<.001$. The initial fixation position by lexicality interaction was not reliable, $F<1$. As shown in Fig. 1(B), words as well as pseudowords were identified most quickly if fixated initially at their center or slightly left thereof: For words, post-hoc tests revealed reliable differences between all adjacent initial fixation positions, all $ps<.05$, except between the 2nd and the 3rd position, $t<1$. For pseudowords, response time differences were at borderline reliability between the 1st and the 2nd position, $p<.07$, differed reliably between the 4th and the 5th position, $p<.01$, but did not differ between the 2nd and the 3rd as well as between the 3rd and the 4th position, ts<1.55.

2.2. Electrophysiological data

2.2.1. First-fixation durations as reflected by EOG

The onset of the saccades resulting in refixations are – as shown in Fig. 2 – reflected in EOG grand means for all initial fixation positions but the 3rd. Differences in saccade lengths (in terms of horizontal eye movements) are reflected by the amplitude of the EOG, with longer saccades for initial fixations on the 1st and 5th letter and shorter saccades for the 2nd and 4th letter. Inverse direction of saccadic eye movements for the 1st and 2nd as compared to the 4th and 5th position is indicated by negative and positive voltages, respectively. This inverse direction of saccades starting from the beginning and

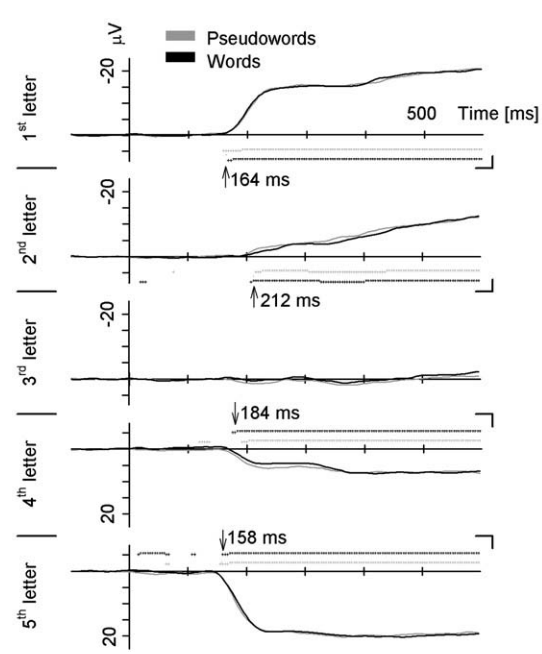

Fig. 2 – Onset of saccadic eye movements as reflected by the EOG for words (black) and pseudowords (grey), plotted separately for all five initial fixation positions. Reliable differences against zero of point-by-point one-sample *t*-tests are indicated ($^+p<.05$; $^*p<.01$).

the end of a stimulus shows that saccades were directed towards the center of the stimulus.

To determine the temporal onset of saccades, the magnitude of the EOG was (separately for initial fixation position and lexicality) compared against zero for each sample point, resulting in a series of point-by-point one-sample *t*-tests every 4 ms (corresponding to the sampling rate of 250 Hz). The results of these consecutive *t*-tests are plotted in Fig. 2 with statistical thresholds below $p<.05$ and $p<.01$ being marked separately. This approach was hyper-sensitive (detecting even

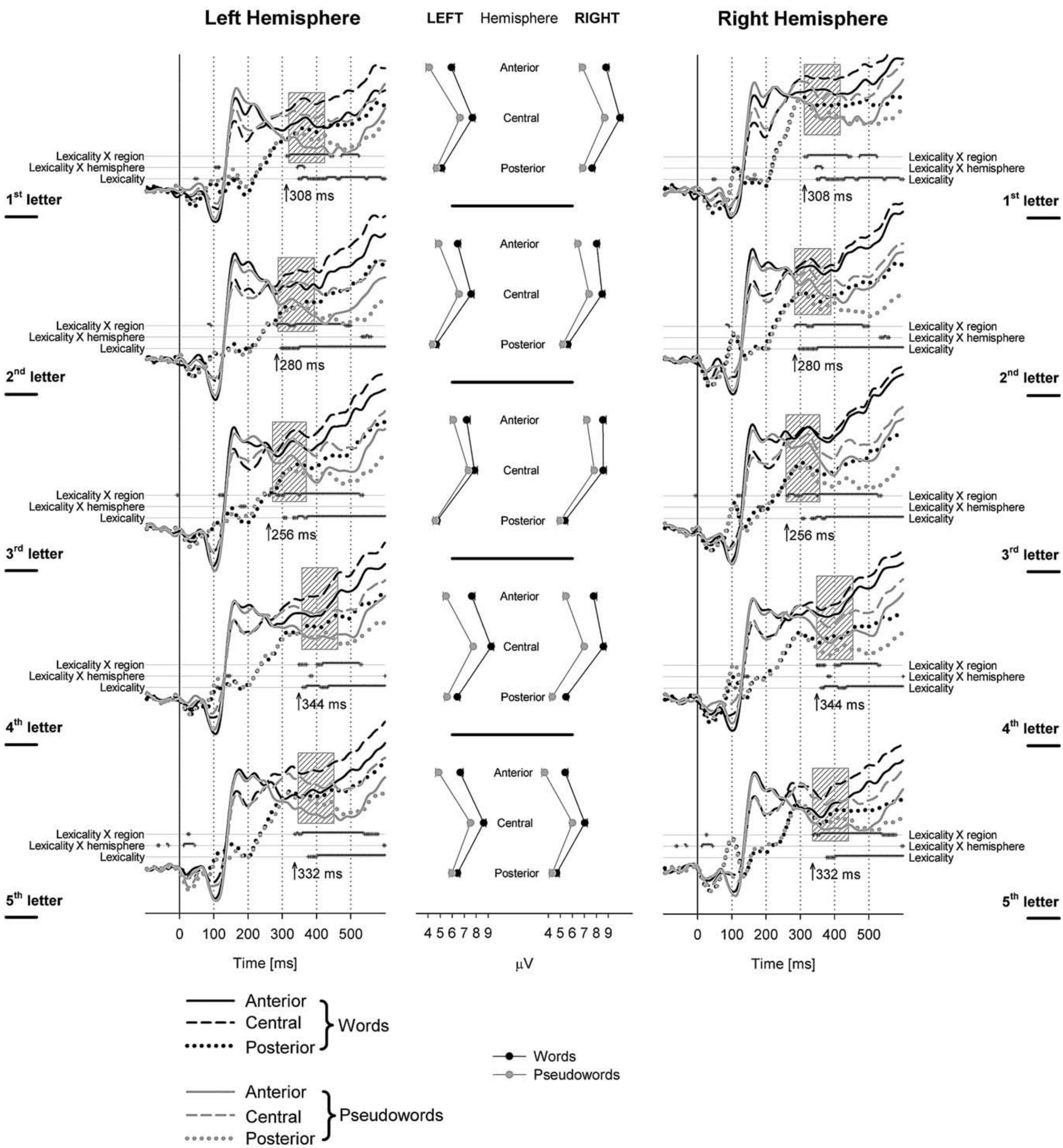

Fig. 3 – Activity of the topographic clusters plotted separately for i.) words [black] vs. pseudowords [grey], ii.) left and right hemisphere [left and right side of the figure], and iii.) the five initial fixation positions [rows from top to bottom]. For the point-by-point 3 way ANOVA, reliable results for the main effect of lexicality and the interactions involving lexicality are indicated ($^+$, $p<.05$; *, $p<.01$). To facilitate interpretation, the *same* results are plotted twice, once for the left and once for the right hemisphere. Time windows of 100 ms duration, determined individually for each initial fixation position on the basis of a continuous effect involving lexicality are highlighted. For illustration, mean amplitude of the respective time windows are plotted in the middle of the figure, separately for lexicality, region, and hemisphere.

smallest deviations, e.g., early differences at the 5th letter for words) and also allowed to reliably determine the onset of smaller saccades exhibited for the 2nd and 4th position. Clearly, because of a α-inflation, statistical differences were only interpretable in case of a considerable number of *t*-tests being reliable in series. Both, the EOG grand means plotted in Fig. 2 and the consecutive *t*-tests indicate that, irrespective of initial fixation position, first-fixation durations did not differ between words and pseudowords. Collapsed for words and pseudowords, the mean onset of saccades for words and pseudowords was 164 ms for the 1st position, 212 ms for the 2nd position, 184 ms for the 4th position, and 158 ms for the 5th position.

2.2.2. *Event related potentials (ERPs)*

The main aim of the ERP analysis was to determine the onset of the lexicality effect as a marker of lexical access. Since the theoretically relevant question was whether the onset of the lexicality effect could be *early* enough to potentially influence the refixation behavior in the *variable viewing position paradigm*, a lenient analysis was chosen to reveal the earliest effects of lexicality. To obtain maximal statistical sensitivity, point-by-point repeated measures ANOVAs with lexicality (words vs. pseudowords), region (frontal, central, posterior) and hemisphere (left vs. right) as within-subject factors were performed for every sample point (i.e., every 4 ms) separately for all five initial fixation positions. The topographic clusters were based on mean values for electrodes in the left anterior (F3, FC1), right anterior (F4, FC2), left central (C3, CP1, and CP5), right central (C4, CP2, and CP6), left posterior (P3, P7), and right posterior (P4, P8) region, roughly corresponding to the clusters used by Barber et al. (2004) and Hutzler et al. (2004). In Fig. 3, activations for the topographic clusters are plotted separately for the left and the right hemisphere and separately for all initial fixation positions.

Reliable results of the main effect of lexicality, the lexicality by hemisphere interaction, and the lexicality by region interaction of the point-by-point ANOVAs are plotted (twice and redundant) for each of the initial fixation positions in Fig. 3. For all initial fixation positions, the onset of a continuous effect started with a reliable lexicality by region interaction, followed by a main effect of lexicality. Of importance here is that the statistical analysis comprised the comparison of brain potentials to words and pseudowords that were initially fixated at the *same* letter position — thereby eliminating any possible systematic influence of eye movements on brain potentials (in the unlikely case of such artifacts being missed by the correction via ICA). The onset of a reliable, continuous lexicality by region interaction was at 308 ms for the 1st position, at 280 ms for the 2nd position, at 256 ms for the 3rd position, 344 ms for the 4th position, and 332 ms for the 5th position. For illustrative reasons, mean amplitudes of 100 ms time windows starting at the above mentioned onsets are plotted in the middle of Fig. 3.

3. Discussion

The aim of the present study was to shed light on the controversial question whether or not the refixation-OVP and the first-fixation duration I-OVP effects are sensitive to word characteristics. For that reason, the relative temporal succession of lexical processes involved in visual word recognition and the deadline up to which the motor program of a saccade (resulting in a refixation as reflected by the refixation-OVP effect) can still be modified were explored. The initial fixation position on a word was experimentally varied by means of the *variable viewing position paradigm* and two brain-electrical markers for the aforementioned processes were assessed: i) the lexicality effect on ERPs was chosen as an indicator for lexical access, ii) the onset of saccadic eye movements as reflected by the EOG was used to back-calculate the deadline for the programming of a saccade resulting in a refixation. To illustrate the subsequent discussion of the effect of initial fixation position, Fig. 4 provides a summary of the results of the present study.

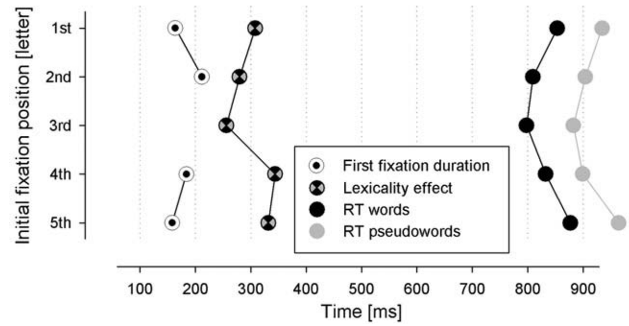

Fig. 4 – The effect of initial fixation position on the duration of the first fixation, the onset of the lexicality effect and on the response times for words and pseudowords.

3.1. *Replication of behavioral OVP and I-OVP effects*

In our study, the standard OVP effects on speed and accuracy of visual word recognition could nicely be replicated: Responses were faster and more accurate if stimuli were initially fixated close to their center. An important finding for the upcoming interpretation of our ERP effects is that the response time advantage of a stimulus initially fixated at its center compared to a stimulus initially fixated at the last (i.e., fifth) letter was about 75 ms. Furthermore, and most importantly, EOG recordings revealed an I-OVP effect for first-fixation duration: First fixations on the 1st and the 5th letter of a word were shorter than those on the 2nd and the 4th letter, respectively. Of theoretical relevance is the fact that the first-fixation duration I-OVP effect was not modulated by the lexical characteristics of the stimulus material. Due to the presentation of isolated words, the durations of initial fixations in the center of the word could not be assessed: Once fixated at the position optimal for information extraction, the participants' gaze remained steady on the stimulus until button press.

3.2. *OVP effects on lexical access*

A novel finding is that the onset of the lexicality effect (estimated by ERPs) was modulated by the initial fixation position. The earliest onset of the lexicality effect was around 256 ms when a stimulus was initially fixated on its center and became more delayed with increasing eccentricity—resulting in an onset at 332 ms for a stimulus initially fixated on the 5th letter. Of specific interest is the finding that the OVP effect on lexical access closely mirrored the magnitude of the response time advantage of the behavioral OVP effect: If initially fixated on its center, lexical access for a stimulus occurred 76 ms earlier as compared to an initial fixation on the last letter. This lexicality-OVP effect is of importance for two reasons. First of all, and of general relevance, is the mere fact that initial fixation position does systematically affect the lexicality effect, thereby further validating brain potentials as an appropriate marker for lexical access. Second, and of specific relevance for the present study, is the magnitude of the lexicality-OVP effect when trying to establish a timeline of processes contributing to the OVP and I-OVP effects—as demonstrated below.

3.3. Opposite effects of eccentricity

When trying to temporally relate the availability of lexical information and the preparation of a saccadic motor program, one has to take into account that with greater eccentricity (i.e., distance to the word center) not only first-fixation duration decreases (as indicated by the I-OVP effect), but also the time necessary for lexical access increases (as indicated by the lexicality-OVP effect). Because of these opposite effects, the temporal gap between the deadline for saccade programming and the availability of lexical information increases with greater eccentricity: If fixated at word center, i.e., at the optimal position, brain potentials estimate lexical access to occur around 256 ms. If fixated at the last letter, brain potentials indicate lexical access to occur as late as 332 ms, while first-fixation duration shrunk to 158 ms, resulting in a temporal gap of around 174 ms.

Such a time interval challenges the idea that lexical information influences the programming of refixations. Although an estimate of lexical access occurring around 256 ms for stimuli fixated at the OVP – as found in the present study – is in accordance with evidence from other studies (e.g., Hutzler et al., 2004), some studies also suggest an earlier availability of lexical information. For example, Sereno et al. (1998) or Pulvermüller et al. (2001) propose that lexical information is available as early as 100 ms post-stimulus. Even when considering lexical access to occur at around 100 ms at the OVP, one still would have to take into account a delay of around 76 ms for an initial fixation position on the last letter (due to increasing eccentricity)—thus ending up with an estimate for lexical access at around 176 ms for suboptimal positions. However, lexical information being available around 176 ms for a stimulus initially fixated on the last letter is still unlikely to systematically influence the where and when of a saccade starting at around the same time: The deadline for the modification of the motor program ends around 50 ms prior to the onset of the actual eye movement (Sereno and Rayner, 2003; Sereno et al., 1998), i.e., at a point in time of around 118 ms—58 ms before lexical information would have been available.

3.4. Two different cohorts of refixations

In the present study, the first-fixation duration I-OVP curve was not modulated by lexical characteristics and on the basis of the above considerations it appears to be highly unlikely that the refixation-OVP effect or the first-fixation duration I-OVP effect as observed with the *variable viewing position paradigm* can be modulated by lexical characteristics at all: Even when considering the earliest lexical effects on ERPs as reported in the literature as a lower limit, lexical information would not have been available to influence the where and when of a saccade resulting in the second fixation. At first sight, these results seem to fuel the ongoing debate as outlined in the Introduction with additional, controversial evidence. However, a closer examination of the findings from this as well as from previous studies suggests that the evidence is complementary rather than controversial.

At the core of the controversy is the temporal gap between the availability of lexical information on the one hand and the onset of saccadic eye movements on the other hand. One determinant of the temporal gap, the moment of availability of lexical information was already discussed and a potential, earlier alternative was considered. But also the second determinant, the temporal onset of the saccade, warrants a closer inspection. In the present study, the duration of the first fixation at the last letter was around 158 ms. Although surprisingly short, this duration is in accordance with those observed in other studies using the *variable viewing position paradigm*: Vitu et al. (2007) reported first-fixation durations starting around 175 ms, O'Regan et al. (1984) and O'Regan et al. (1986) around 170 ms. These rather short first-fixation durations stand in marked contrast to the duration of first fixations as observed during the continuous reading of text. For English, first-fixation durations around 240 ms are reported (e.g., Inhoff, 1984). Even for German, as an example for a transparent orthography, first-fixation durations of 201 ms and 190 ms are reported (for right-directed and left-directed refixations in multi-fixation cases, respectively, Kliegl et al., 2006). For a better understanding of these apparent discrepancies concerning the duration of first fixations, it is helpful to compare the specificities of the *variable viewing position paradigm* with the specificities of a different paradigm that also involves the recognition of isolated words, for instance, the study by Pynte (1996). In Pynte's study, refixations on words were preferentially directed towards the region of a word that contained the letters that were crucial for disambiguation among lexical competitors. Furthermore, and of theoretical importance, the durations of first fixations were around 300 ms. The crucial difference, however, was that in Pynte's study the position of the initial fixation was experimentally placed at an optimal position – in contrast to the *variable viewing position paradigm* in which the position of the initial fixation is intentionally shifted to suboptimal positions. As a consequence, the two paradigms might predominantly capture two different cohorts of refixations – probably being caused by different mechanisms.

In the *variable viewing position paradigm*, the lower level prerequisite for successful word recognition, i.e., an initial fixation position guaranteeing adequate visual perception, is not given — and therefore has to be obtained by means of a

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refixation. In this setting, saccade onset probably is triggered by lower level visual processes and – occurring relatively early – is unlikely to be modulated by lexical characteristics. In contrast, in Pynte's (1996) setting, the initial fixation is optimal in terms of visual perception, therefore not requiring refixations driven by lower level visual processes. Rather, these refixations might be triggered by higher-level cognitive processes, the onset of saccades being relatively late and thus likely to be sensitive to lexical information.

The assumption of two different cohorts of refixations is supported by a secondary finding in Vitu et al.'s (1990) study during which participants were presented with words embedded in larger strings of symbols using the *variable viewing position paradigm*: Characteristics of early refixations (around 175–200 ms) were "string based", that is, not influenced by lexical characteristics, whereas later refixations (around 325 ms) were "word based". Additional evidence for the existence of two different cohorts of refixations is provided by a study of Vergilino-Perez et al. (2004) who could provide evidence for rather short initial fixations (less than 200 ms) that are followed by corrective saccades towards the center of the word in order to correct for oculomotor errors. The notion of subpopulations of refixations of different causality is not a new one; Rayner et al. (1996) already suggested two of those subpopulations. First, refixations due to initial fixation positions (those suspected to be caused by inaccurate eye movements, Pollatsek and Rayner, 1990) at which maximal information cannot be obtained (similar to a suggestion that 8% of all refixations are due to other reasons than failure in word recognition, McConkie et al., 1989), and second, refixations due to difficulty in accessing the appropriate meaning of a word.

3.5. *Natural reading*

During natural reading, a reader's initial fixation is neither always at an optimal nor at a suboptimal position. As a consequence, during natural reading we will most probably observe refixations of both, the early and the late cohort. This, in turn explains why for the refixation–OVP curve as observed during continuous reading (in contrast to that observed with the *variable viewing position paradigm*) potential influences of lexical characteristics are reported: For the continuous reading of text, McConkie et al. (1989) reported a potential influence of word-frequency on the vertical offset of the refixation–OVP curve (though stating the necessity for a closer examination by means of a larger data set) and Vitu et al. (1990) observed small effects of word-frequency on refixation–OVPs. The overall pattern of refixations during natural reading therefore reflects (diminished) OVP and I-OVP effects that can also be modulated by lexical characteristics. Although the cohort of early corrective refixations might not always be observable in its pure form during natural reading, it is of importance that the present study revealed its existence: Corrective refixations that are not influenced by lexical characteristics of the actually fixated stimulus are most probably part of eye movements also during natural reading and need to be acknowledged for. These refixations should resemble first fixations in two-fixation or multi-fixation cases (but not single-fixation cases) since the corrective refixations seem to be directed towards the center of the actually presented stimulus.

3.6. *Implications for models of eye movement control in reading*

The theoretically relevant question is now how current models of eye movement control in reading can account for our results. The present study provided evidence for an early cohort of refixations during reading i.) which corrects for suboptimal initial fixation positions, ii.) whose saccade latency (and thereby the duration of the antecedent, first fixation) is dependent on the initial fixation position, and iii.) which is not affected by the lexical characteristics of the actually fixated stimulus. The refixation–OVP and the first-fixation duration I-OVP effect, like two sides of the same coin, resemble this cohort of corrective refixations. In the following discussion on models of eye movement control, however, we will focus on the first-fixation duration I-OVP effect to put the different models to the test. More specifically, the question is, whether (under ideal, to be defined circumstances) these accounts are capable to model a first-fixation duration I-OVP curve that is not modulated by lexical characteristics.

Prior to the evaluation of current computational implementations of models of eye movement control, it is important to state that the claim of an early cohort of corrective refixations is compatible with the *perceptual economy* account for the I-OVP effect (Vitu et al., 2007; Vitu et al., 2001). Vitu and colleagues proposed that fixations that constitute the first-fixation duration I-OVP effect are autonomous with regard to ongoing word recognition processes, are based on early available visual cues, and serve the needs of ongoing word identification process (Vitu et al., 2007). The *perceptual economy* hypothesis will be considered again below when reconsidering a successful computational implementation of the I-OVP effect.

The *SERIF* model's central conceptual feature is the implementation of a split fovea and resultant projection of information to the respective contralateral hemisphere (McDonald et al., 2005). The duration of a fixation, as realized by SERIF, is determined by five empirically motivated key mechanisms. Due to the specific computational implementation of these mechanisms, only one, the influence of parafoveal preview benefit (i.e., *prior probability*) is not affected by the lexical characteristics of the stimulus. Two further mechanisms, *visual familiarity* (which directly reflects word-frequency) and the hemisphere specific *information content* (which is a lexicon based statistic of letter sequences that resembles the amount of information that is projected in each hemisphere) are clearly influenced by lexical characteristics. An indirect influence of word characteristics can be found for the remaining two mechanisms: The so called *dynamics of the random rise rate* (which basically realize a small temporal correlation in latencies across successive saccades) and the *interhemispheric lateral inhibition* (which realizes reciprocal inhibition between the two hemispheres). In the case of SERIF, the first-fixation duration I-OVP effect is generated by an interplay between hemisphere specific *information content* and *interhemispheric lateral inhibition*: If a stimulus is initially fixated close to its center, the value of the *information content* which is projected in the two hemispheres is comparable. Due to the principle of *interhemispheric lateral inhibition*, the comparable values in both hemispheres result in increased lateral inhibition and, in turn, in prolonged first fixations. In contrast, if a stimulus is initially fixated at either beginning or end, the *information content* projected in the two hemispheres differs. In this case *interhemispheric lateral inhibition* is reduced and first fixations are shorter. Of theoretical importance is that the five core mechanisms exert their influence on fixation duration simultaneously and there is no delay in the availability of lexical information. Therefore, lexical characteristics of the stimulus will influence the duration of even shortest fixations. Thus, SERIF would predict that early corrective eye movements are modulated by lexical characteristics of the stimulus material—in contrast to the findings of the present study.

The *E-Z Reader model* (Pollatsek et al., 2006) explicitly accounts for corrective refixations in the case of initial suboptimal fixation positions which do not allow efficient processing because of poor visual acuity (Pollatsek et al., 2006, p. 15). To accelerate lexical processing, a rapid saccade is supposed to move the eye closer to the center of the word. Such a corrective refixation can be cancelled if an early stage of word identification (i.e., the *familiarity check*) is completed. Of importance here is that (according to the authors, Pollatsek et al., 2006, p. 50) it is particularly the different speed with which the *familiarity check* proceeds at different initial fixation positions (and the resultant different probabilities of canceling a corrective refixation) that constitutes the basis for I-OVP effect. With the *familiarity check* generating the actual shape of the I-OVP curve, it has to be assumed that the first-fixation duration I-OVP curve as modeled by E-Z Reader would be modulated by the lexical characteristics of a stimulus. The E-Z Reader model therefore most probably cannot account for our findings. In the absence of concrete model simulations using E-Z reader and our data, this inference, however, remains preliminary.

The proponents of the *SWIFT* model (e.g., Engbert et al., 2005) initially interpreted the first fixation-duration I-OVP effect as reflecting error correction following upon mislocated fixations on unintended words (for empirical evidence, see, Nuthmann et al., 2005, 2007). Interestingly, in the Appendix of the latest presentation of SWIFT, the authors demonstrated its capability to model also the first-fixation duration I-OVP effect for two-fixation cases, i.e., within-word refixations. For a better understanding of this demonstration a short introduction of two of SWIFT's core principles is helpful. *Error correction of mislocated fixations* (i.e., Principle 6) was initially implemented to detect whether an unintended word was erroneously fixated. Because this error correction is based on the comparison of the intended saccade program with an efferent copy of the motor signal to the eye muscles (Engbert et al., 2005, p. 787) it is also capable to detect saccadic errors in the case of unintended fixation locations *within* a word (Engbert et al., 2005, p. 810). A further core principle, *latency modulation of saccade programming due to intended saccade amplitude* (i.e., Principle 7), introduces an inverse relationship between the intended saccade amplitude and saccadic latency: The smaller an intended saccade amplitude, the higher is the necessary saccade programming time (Engbert et al., 2005, p. 786). Engbert et al. (2005, p. 810) could show that the interplay of these two principles allows to model the first-fixation duration I-OVP effect also for two- or multi-fixation cases, i.e., for corrective refixations within a word. The remaining question is now, whether the I-OVP curve for two- or multi-fixation cases as modeled by SWIFT is modulated by the lexical characteristics of a stimulus. A possible answer can be found in the way by that error correction of mislocated fixations (i.e., Principle 6) is implemented: In the case of the detection of a mislocated fixation, the autonomous timer is overruled and a saccade program is started immediately (Engbert et al., 2005, p. 781). Importantly, in the SWIFT model, top-down influence from the lexical processing module is exerted by a *delay* of the *initiation* of a new saccade program. An *immediate initiation* of a new saccade program upon Principle 6 therefore should annul the influence of lexical processing. Therefore, no influence of lexical properties on the duration of first fixations in the case of early, corrective refixations should be found. Again, this inference is preliminary and requires actual modeling work for clarification.

3.7. Conclusion

The first-fixation duration I-OVP curve observed in the present study was not modulated by the lexical characteristics of the actually fixated stimulus. An analysis of the temporal succession of the availability of lexical information on the one hand and saccade programming deadline on the other hand furthermore revealed that it is highly unlikely that first-fixation duration I-OVP and refixation–OVP effects as observed with the *variable viewing position paradigm* can be modulated by lexical information at all. It was suggested that both, OVP and I-OVP effects are most probably based on an early cohort of refixations that is not influenced by lexical information and that resembles a part of natural reading. E-Z Reader as well as SWIFT both explicitly acknowledge for these corrective refixations. A crucial difference, however, can be found in the way in that both models account for the I-OVP curve. SWIFT's core mechanism accounting for the I-OVP effect is that the planning of saccades with rather short amplitudes results in greater processing time — a physiological plausible assumption that is based on empirical evidence (Wyman and Steinman, 1973). Due to that basic oculomotor (non-cognitive) mechanism, SWIFT can account for early corrective refixations that are not influenced by the lexical characteristics and as a consequence, SWIFT can model an I-OVP curve that is not modulated by word-frequency. In contrast, E-Z Reader would predict such an influence. Interestingly, the characteristics of the early cohort of corrective refixations as realized by SWIFT are compatible with the perceptual economy account. The variable viewing position paradigm, furthermore, proved to be a suitable tool for the exploration of the characteristics of a specific cohort of refixations during reading. Although eye movements as observed by the *variable viewing position paradigm* are not representative for natural reading, this paradigm does allow to observe and to experimentally manipulate an early cohort of corrective refixations that is part of natural reading.

4. Experimental procedures

4.1. Participants

Seventeen native German-speaking students (all female) of the Freie Universität Berlin (mean age 27 years) with normal or corrected to normal vision participated in the study.

4.2. Experimental paradigm

In the present study, the initial fixation position on five-letter words and pseudowords presented in isolation during a lexical decision task was varied from the 1st to the 5th letter by means of the *variable viewing position paradigm* (O'Regan et al., 1984).

4.3. Stimuli

The characteristics of the stimulus material were matched across the five *initial fixation positions* and the two different response-hand assignments. Thus, 300 five-letter words and 300 pseudowords were assigned to 10 bins each (initial fixation position [5]×response-hand alteration [2]). For words, these 10 bins were matched on word-frequency ($M=41.14$; $SD=93.35$), bigram-frequency ($M=5453$; $SD=4840$) and neighborhood size ($M=1.98$; $SD=1.94$). An item-based ANOVA with bin (1 to 10) as between-item factor revealed no differences, all $Fs<1$. For pseudowords, these 10 bins were matched on bigram-frequency ($M=6092$; $SD=7598$) and neighborhood size ($M=2.73$; $SD=1.80$), again all $Fs<1$. The 10 bins of words and pseudowords were randomly assigned to the 5 different initial fixation position conditions and the 2 response-hand assignments.

4.4. Procedure

Each trial started with a screen indicating allowance for eye blinks (1600 ms) and a blank screen (varying between 1000 and 1500 ms to prevent phase lock on trial timing). followed by two vertical fixation lines (height: 8 mm, duration: 1000 ms) and a blank screen (50 ms). Subsequently, the experimental stimulus was presented for 100 ms, followed by a blank screen (1500 ms). The horizontal position of the stimulus was varied in a way that the *to-be-fixated* letter was in the position between the (already disappeared) fixation lines. To ensure constant letter spacing, stimuli were presented in uppercase Courier font on black background in white color. Letters were of 8 mm height and 7 mm width, corresponding to a vertical visual angle of 0.9° and a horizontal visual angle of 0.8°. Participants were instructed to indicate as fast and as accurately as possible, whether a stimulus was a word or a pseudoword. Response buttons were pressed with the left and right index finger. After the presentation of half of the experimental stimuli, the response-hand assignment (left vs. right index finger) to words and pseudowords was inversed, the initial response-hand assignment being counterbalanced across participants. To familiarize the participants with the task demands, 10 practice trials preceded the first and the second half of the experimental stimuli.

4.5. Apparatus

Multichannel EEG was recorded from 27 Ag/AgCl electrodes mounted with a modular elastic cap (Easy Cap, Falk-Minow Systems, Germany) on standard positions according to the 10–20 systems. Signals were amplified by a 32 channel Brainamp (BrainProducts, Germany) amplifier with a .01–70 Hz band pass and a 50 Hz notch filter. Scalp electrodes were recorded referentially against linked earlobes (as common reference) with a sampling rate of 250 Hz. To monitor horizontal and vertical eye movements, EOG was recorded bipolar from the outer canthus of each eye as well as from above and below the right eye, respectively. Impedances for scalp electrodes were kept below 5 kΩ. Participants were seated in a distance of 50 cm from a 17" CRT monitor connected to an IBM compatible computer. Stimulus presentation was controlled by Presentation (Neurobehavioral Systems, CA) software.

4.6. Analysis of event-related potentials

For the analysis of event-related potentials (ERPs), continuous EEG data was segmented from 100 ms pre-stimulus to 600 ms post-stimulus. Trials corrupted by eye blinks or EEG-artifacts (determined by visual inspection, 3.54%) were excluded from further analysis as were trials with incorrect responses (see Results section for proportion of errors). For baseline correction, a 100 ms pre-stimulus interval was chosen and ERPs were calculated separately for words and pseudowords and for all five initial fixation positions. To check for possible artifacts of the (due to the experimental manipulation inevitable) horizontal eye movements in brain potentials, independent component analysis (ICA) was performed (Vigario, 1997). By means of ICA, waveforms are separated into components that are maximally independent from each other. The ICA component resembling the typical activity pattern and component map of horizontal eye movements is then removed prior to back-projection (see also Delorme et al., 2007). ICA has been shown to be useful for the identification and elimination of the horizontal eye movements typical for reading in previous studies (Hutzler et al., 2007). In the present study, however, no component representing horizontal eye movements could be identified. The reason most probably lies in the eye movements' small magnitude: A variable viewing position paradigm using 5 letter stimuli typically results in horizontal eye movements subtending 2 letters at maximum (corresponding to a visual angle of 1.6 degree). Statistical analysis comprised the comparison of brain potentials in response to words and pseudowords with an initial fixation on the *same* letter, thereby canceling out potential artifacts resulting from horizontal eye movements (see Results section).

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