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Research Report

Synchronizing timelines: Relations between fixation durations and N400 amplitudes during sentence reading

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ABSTRACT

We examined relations between eye movements (single-fixation durations) and RSVP-based event-related potentials (ERPs; N400s) recorded during reading the same sentences in two independent experiments. Longer fixation durations correlated with larger N400 amplitudes. Word frequency and predictability of the fixated word as well as the predictability of the upcoming word accounted for this covariance in a path-analytic model. Moreover, larger N400 amplitudes entailed longer fixation durations on the next word, a relation accounted for by word frequency. This pattern offers a neurophysiological correlate for the lag-word frequency effect on fixation durations: word processing is reliably expressed not only in fixation durations on currently fixated words, but also in those on subsequently fixated words.

1. Introduction

Eye tracking and EEG hold the potential to deliver precise timelines of word recognition during reading. Here we show how their joint consideration takes advantage of their respective strengths and yields novel insights into this process.

Tracking eye movements provides accurate information about where the eyes look at a given moment. When an individual reads a text, a word is fixated for approximately 200 to 250 ms before a saccade is made and the next word is fixated. The time spent on a given word strongly depends on the ease with which the stimulus can be processed (see Rayner, 1998 for a review). For instance, words rarely occurring in a language (i.e., low-frequency words) are fixated longer than common (high-frequency) words. Also contextual information affects reading speed. Words are fixated longer when they are not or hardly predictable compared to high-predictable words[1] (e.g., Inhoff and Rayner, 1986; Kliegl et al., 2004; Kliegl et al., 2006; Rayner et al., 2001; Rayner and Well, 1996; Schilling et al., 1998). The instantaneous influence of properties of a fixated word n on inspection durations on word n is known as *immediacy effect*.

Moreover, spillover or *lag effects* during reading characterize word properties affecting fixation durations on the next word. For instance, fixation durations on word n are longer when the preceding stimulus (i.e., word $n-1$) was of low frequency (Kliegl et al., 2006; Schroyens et al., 1999). Kliegl et al. reported that low predictability lengthens fixation durations on a subsequent word as well, but this effect was smaller than the lag-frequency effect. One explanation for lag effects is that word recognition might not be finished during fixation time. Kolers (1976; see also Bouma and de Voogd, 1974) proposed that fixation durations

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[1] Predictability usually measured in a cloze task is the proportion of people correctly predicting a word from a given context.

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between 150 and 300 ms are too short to grant full language comprehension. Instead, the mind lags behind the eyes. According to this *cognitive lag hypothesis* (Rayner, 1977, 1978), linguistic processing continues while the eyes have already moved on to the next word.[2] Processing incompleteness of word $n-1$ spills over and causes longer fixation durations on word n. As incomplete processing is more likely for difficult stimuli, longer fixation durations occur predominantly after low-frequency words. This interaction between frequency of word $n-1$ and word n has been obtained in nine eye-tracking experiments after statistical control of a large number of alternative sources of variance (Kliegl, 2007).

In addition to immediacy and lag effects, properties of upcoming words within the perceptual span (e.g., word $n+1$) exert reliable influences on fixation durations on word n, so-called *successor effects*. Despite much controversy whether inspection time on word n is modulated by sublexical or lexico-semantic features of a not yet fixated, parafoveal word $n+1$ (e.g., Kennedy and Pynte, 2005; Rayner et al., 2003; Vitu et al., 2004), a novel successor effect has been reported recently: Fixation durations on word n are longer when word $n+1$ is high-predictable (Kliegl et al., 2006). Since predictability is generated before a word is fixated[1], information about a highly predictable word $n+1$ may be extracted from memory while the eyes are resting on word n. Memory retrieval then may make unnecessary a saccade to word $n+1$ and prolong inspection duration on word n. Consequently, no or only minimal visual information may be necessary to access a high-predictable word $n+1$ during the fixation of word n. In a subsequent analysis of this data, the positive correlation of single-fixation duration on word n and predictability of word $n+1$ was linked primarily to constellations where word n or word $n+1$ was a function word (Kliegl, 2007).

Besides eye tracking, the measurement of event-related potentials (ERPs) is a valuable instrument for the investigation of reading processes. ERPs provide an online measure of neural activity with excellent temporal resolution (for reviews see Kutas and Federmeier, 2000; Kutas and Van Petten, 1994; Kutas et al., 2006). One of the best documented ERP components is the N400, a negative deflection most prominent over centro-parietal sites in an epoch from approximately 300 to 500 ms (e.g., Kutas and Hillyard, 1980, 1983). The N400 is sensitive to the ease with which words are processed. Low-frequency as well as low-predictable words evoke larger N400 amplitudes than high-frequency or high-predictable words (e.g., Dambacher et al., 2006; Rugg, 1990; Van Petten, 1993; Van Petten and Kutas, 1990). Fig. 1 illustrates these effects for data of the present study (i.e., a subset of data from Dambacher et al., 2006; see Experimental procedures).

In an ongoing debate on its functional nature, several authors argued that the N400 peak latency occurs too late to reflect lexical processes like word recognition. On the assumption that a word is usually lexically accessed before the eyes leave it, and given an average fixation duration of about 200 to 250 ms during normal reading, the N400 must be associated with post-lexical integration (e.g., Brown and Hagoort, 1993; Holcomb, 1993; Sereno and Rayner, 2003; Sereno et al., 1998). However, N400 amplitude effects often start at around 200 ms post-stimulus, a time when difficult words even during normal reading are still fixated. Moreover, empirical evidence for sensitivity to lexico-semantic processes in priming studies suggests that the N400 does not purely reflect post-lexical integration (e.g., Deacon et al., 2004; Deacon et al., 2000). Also, reports of larger N400 predictability effects for low- than for high-frequency words indicate that frequency as lexical (bottom–up) and predictability as post-lexical (top–down) variable affect the same stage of word recognition (Dambacher et al., 2006; Van Petten, 1993, 1995; Van Petten and Kutas, 1990). Dambacher et al. proposed that lexical access of difficult words extends into the N400 epoch. In this time range, processing of low-frequency words is strongly supported by predictability.

Both eye movement measures and ERPs separately contribute to the understanding of word recognition. Of course, combining the two measures, namely recording eye movements and ERPs simultaneously from the same subjects within one experiment, would achieve even better insights into the timeline of reading processes (Sereno and Rayner, 2003). Unfortunately, several problems render a co-registration very complex. First, EEG signals are contaminated by eye movements during normal reading. The eyes can be thought of as dipoles, which are positive towards the cornea. When an eyeball alters orientation, voltage changes due to the movement are gradually propagated back over the scalp. Also blinks cause substantial artifacts because closing eyelids connects frontal scalp sites to the positively charged cornea (Lins et al., 1993). Therefore, in EEG studies, stimuli are often presented at a fixed position making eye movements unnecessary. Furthermore, participants are asked not to blink, which disadvantageously imposes an additional task. Although by now various valuable techniques have been developed to handle eye artifacts in the EEG signal [e.g., Multiple Source Eye Correction (Berg and Scherg, 1994); Independent Component Analysis (Jung et al., 1998)], the second problem of component overlap is severe. Language-related ERP components, like the N400, occur at latencies, when the eyes during normal reading already fixate a subsequent word. If ERPs were recorded at normal reading speed of 200 to 250 ms per word, neural responses evoked by different words would temporally coincide, so effects could not be uniquely attributed to processing of a certain word. Consequently, sentences in ERP experiments are usually presented word by word with unnaturally long intervals between stimuli.

1.1. Present study

One possibility to circumvent these difficulties at least in part is to compare eye movements and ERPs from separate

[2] Several other theories account for lag effects from an eye movement perspective [e.g., reduced parafoveal preview (Balota et al., 1985) or dynamical perceptual span due to foveal load (Henderson and Ferreira, 1990)]. However, these assumptions do not suit the present ERP paradigm of word-wise sentence presentation. Hence, they cannot serve as explanation for lag effects in our linked eye movement and ERP data and are not further discussed here (see Kliegl et al., 2006, for a review).

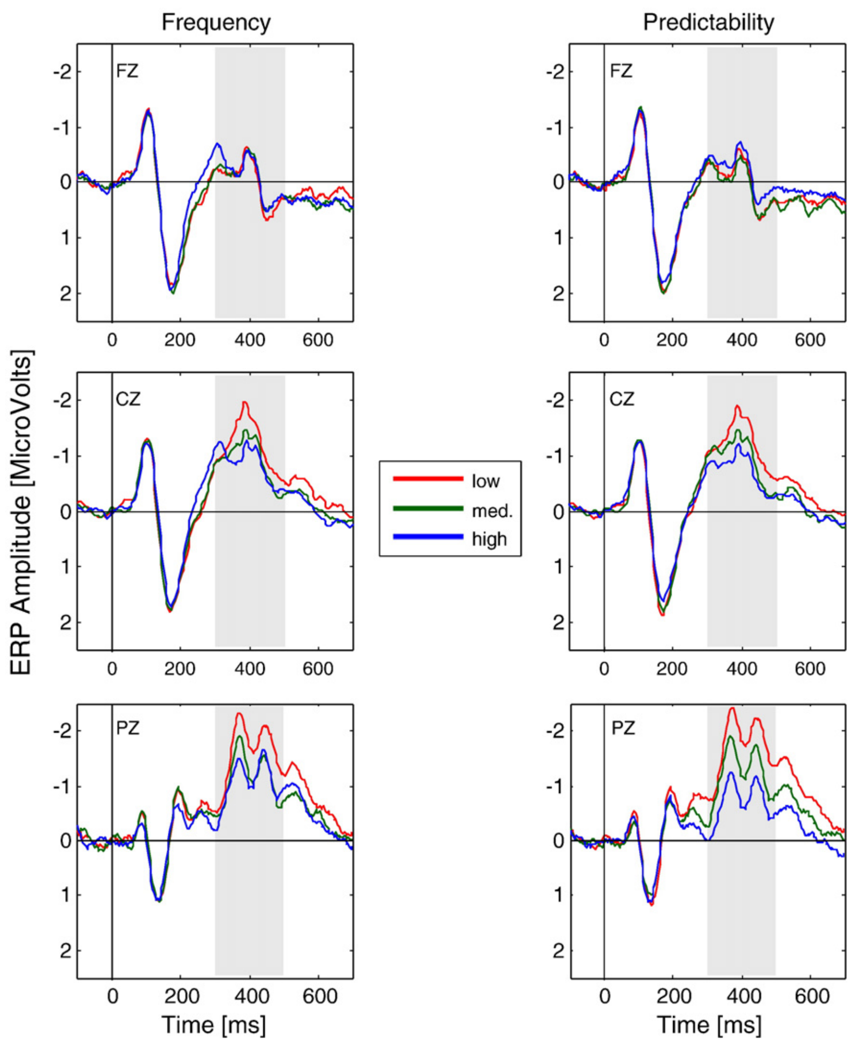

Fig. 1 – Grand average ERPs. ERPs for three categories of frequency (left panels) and predictability (right panels). N400 amplitudes in the epoch from 300 to 500 ms over centro-parietal electrodes are larger for words of low than of high frequency and predictability. Averages are computed on the basis of 48 subjects and 343 open-class words varying between third and antepenultimate position in sentences (see Experimental procedures). Categories (low, medium, high) each comprising approximately one third of the stimuli are computed on the basis of quantiles. Data are from Dambacher et al. (2006).

experiments using similar stimuli (e.g., Raney and Rayner, 1993; Sereno and Rayner, 2003; Sereno et al., 1998). We followed this approach in the present paper. In one experiment, eye movements were recorded during reading of 144 sentences of the Potsdam Corpus (PSC). In another experiment with different subjects, ERPs were assessed while the PSC was displayed word by word, during rapid serial visual presentation (RSVP). We examined relations between fixation durations and N400 amplitudes and determined whether both measures are comparably sensitive to the same mechanisms of word recognition. On the one hand, assuming a tight coupling between the two measures is not trivial because they originate from different sources and techniques: eye movements are behavioral responses from the oculomotor system, while ERPs are indicators of neural activity. On the other hand, fixation durations and N400 amplitudes are clearly associated with central reading processes. First, both measures are modulated by word difficulty: fixation durations as well as N400 amplitudes decrease with high frequency and predictability of words. Second, they mirror relatively late stages of word recognition. Fixation durations mark the point in time, when the eyes leave a stimulus, i.e., when lexical processing relying on visual input from a letter string is terminated. Similarly, N400 amplitudes probably denote one of the final stages of lexico-semantic processing as they are sensitive to lexical but also to post-lexical properties. Thus, fixation durations and N400 amplitudes possibly get input from a common stage of word recognition. If this is true, we should find substantial covariation between the two measures.

We explored the relationship between eye movements and ERPs in path analyses addressing immediacy, lag and successor effects. For immediacy effects, we expected correlations between fixation durations and N400 amplitudes suggesting that both measures are sensitive to the same word recognition processes. If so, frequency and predictability of the corresponding word represent likely determinants for the covariation as both mirror processing difficulty. Conversely, joint sensitivity of eye movements and ERPs to frequency and predictability questions a strict assignment to either lexical or post-lexical processes and favors rather hybrid functions of fixation durations and N400 amplitudes.

Considering lag effects, it is important to note that the N400 usually peaks at a latency when fixation during normal reading is already on the next word. As the N400 reflects processing of its eliciting stimulus, a significant relation between N400 amplitudes and the next fixation would indicate that word recognition continues after the eyes moved on. Tracing this relation to word frequency would then provide a physiological explanation for the lag effect in eye movements, namely that ongoing processing interferes with recognition of the next word (Kliegl et al., 2006; see also Bouma and de Voogd, 1974; Kolers, 1976). At the same time, support for the lag effect as reflection of incomplete processing of prior words holds important implications for the comprehension of reading processes. Several words can be processed simultaneously and influence recognition of each other. Thus, models of oculomotor control (e.g., SWIFT, Engbert et al., 2002; Engbert et al., 2005; E-Z Reader, Pollatsek et al., 2006; Reichle et al., 1998; Reichle et al., 2003) would have to encounter reading as distributed rather than as serial process.

Concerning successor effects, we assumed that predictability of an upcoming word accounts for covariance between eye movements and ERPs. As the cloze task (i.e., the usual procedure to collect predictability norms) explicitly requires the anticipation of a not yet visible word, predictability reflects at least partly the degree of contextual constraint, which determines the certainty of predictions (see also Dambacher et al., 2006). Confident predictions can be made whenever contextual constraint is high, irrespective of the actual identity of the upcoming word. Successor effects have been found as longer fixation durations prior to high-predictable words (Kliegl et al., 2006). Also findings on ERPs point to predictions about upcoming words (DeLong et al., 2005; Van Berkum et al., 2005; Wicha et al., 2003a,b, 2004). Considering fixation durations and N400 amplitude, joint successor effects would indicate that online predictions are made during reading and that a word is potentially retrieved from memory before it is fixated.

2. Results

2.1. *Fixation durations and N400 amplitudes*

The immediacy effect in ERPs and eye movements is visualized as a function of word frequency (left panel) and predictability (right panel) of word *n* (Fig. 2). The bins were computed by dividing continuous frequency and predictability values into five quantiles each comprising approximately 20% of the data. As the high proportion of words not predictable at all could not be further split up into categories (i.e., 42.9% shared the lowest predictability value of −2.55), the first and second quantile merged such that only four bins are displayed on the right panel. Error bars reflect 99% confidence intervals.

Fixation durations (FD_n) as well as N400 amplitudes ($N400_n$) are sensitive to frequency and predictability of word *n*. Moreover, a comparison of the curves for eye movements and ERPs reveals striking similarity. FD_n and $N400_n$ decrease as word frequency increases following a quadratic trend: differences are larger in the low-frequency than in the high-frequency range (the higher-order trends are illustrated in Kliegl et al., 2006, Fig. 3 and in Dambacher et al., 2006, Fig. 4 as

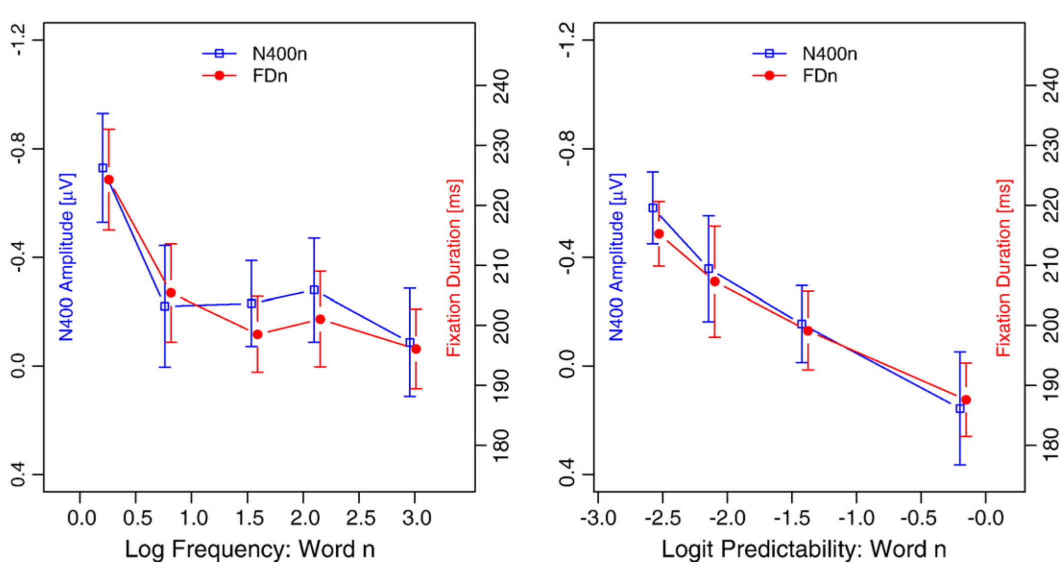

Fig. 2 – Immediate relations: word *n* effects on FD_n and $N400_n$. Mean fixation durations (FD_n) and N400 amplitudes ($N400_n$) of word *n* as function of frequency (left panel) and predictability (right panel) of word *n*. Data points were calculated on the basis of quantiles for frequency and predictability. Error bars reflect 99% confidence intervals. Eye movement data are from Kliegl et al. (2006) and EEG data are from Dambacher et al. (2006).

well). Importantly, both curves show similar disordinalities: the largest drop appears from the first to the second quantile. In the fourth quantile both measures slightly increase, while they decrease again in the fifth quantile. Concerning the right panel, FD_n and $N400_n$ linearly decline as predictability augments.

In addition to the immediate influence of word *n*, lagged frequency and predictability affect fixation durations (cf. Kliegl et al., 2006). Fig. 3 illustrates that FD_n declines as frequency and predictability of the *prior* word $n-1$ increase. Unsurprisingly, also N400 amplitudes of word $n-1$ ($N400_{n-1}$) drop with frequency and predictability of word $n-1$. Thus, Fig. 3 uncovers covariation of FD_n and $N400_{n-1}$ as a function of word $n-1$. Although the visual impression of the lagged relation is weaker than the one for the immediate relation (Fig. 2), the temporal coincidence of $N400_{n-1}$ and FD_n suggests functional relationship between the two variables (see below).

In summary, fixation durations and N400 amplitudes are strongly modulated by frequency and predictability. Therefore, a similar shape of the lines in Figs. 2 and 3 is not unexpected. Note, however, that ERPs and eye movements stem from independent experiments differing in subjects (125 vs. 48), paradigm (normal reading vs. RSVP) and laboratory (University of Potsdam vs. University of Eichstätt-Ingolstadt). Considering that the studies merely shared the stimuli, the high correspondence of the two measures warrants a closer examination of this covariation. The large samples of participants and items constitute a stable and reliable basis for the analyses of otherwise noisy measures of eye movements and ERPs. Furthermore, with identical linguistic material in an item-based analysis, we can control for differences between the studies, which may mask common sources of variance in fixation durations and N400 amplitudes (e.g., large inter-individual differences).

In the following sections we will address several questions: how do fixation durations and N400 amplitudes during sentence reading dynamically relate to each other in a time window including more than the currently fixated word? Is there evidence for mutual influence between fixation durations and N400 amplitudes? Can relationships be traced back to a common stage of word recognition?

2.2. Synchronizing the timelines

Before examining the relations between fixation durations and ERPs, the two measures must be mapped to a common time scale. Fig. 4 illustrates how fixation durations and N400 amplitudes temporally relate to each other. The lower part of Fig. 4a presents a schematic time course of eye movements corresponding to data from Kliegl et al. (2004, 2006); subjects were normally reading sentences from left to right. When the eyes land on a word, it is fixated for about 200 ms before a saccade brings the eyes to the next word, which again is fixated for approximately 200 ms. The upper part of Fig. 4a illustrates an idealized ERP timeline elicited by word *n*. This curve is compatible with the present ERP data with words presented in fixed intervals of 700 ms (see Fig. 1 and Dambacher et al., 2006). The N400 component peaks at a latency of approximately 400 ms after stimulus onset. The blue-shaded area denotes that both FD_n and $N400_n$ are associated with the same stimulus. The common time scale makes clear that the $N400_n$ occurs at a time when the eyes during normal reading already fixate word $n+1$.

On the basis of this scheme, we sketch a pattern about the relation between fixation durations and N400 amplitudes. The lower part of Fig. 4b reflects the timeline of normal reading. The upper part shows two ERP curves, one elicited by word *n* (blue area) and one evoked by word $n-1$

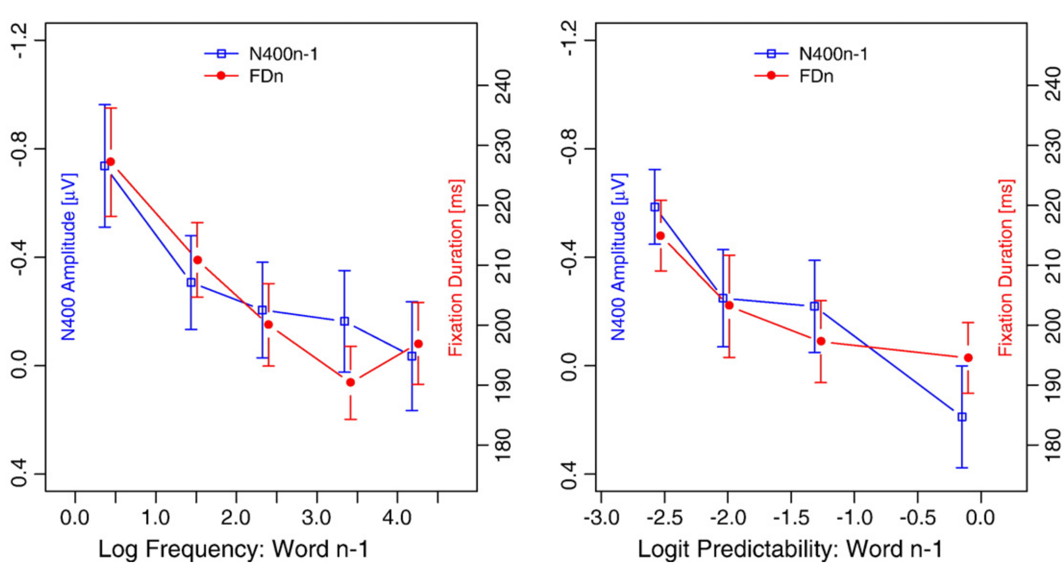

Fig. 3 – Lagged relations: word $n-1$ effects on FD_n and $N400_{n-1}$. Mean fixation durations on word *n* (FD_n) and N400 amplitudes on word $n-1$ ($N400_{n-1}$) as function of frequency (left panel) and predictability (right panel) of word $n-1$. Data points were calculated on the basis of quantiles for frequency and predictability. Error bars reflect 99% confidence intervals. Eye movement data are from Kliegl et al. (2006) and EEG data are from Dambacher et al. (2006).

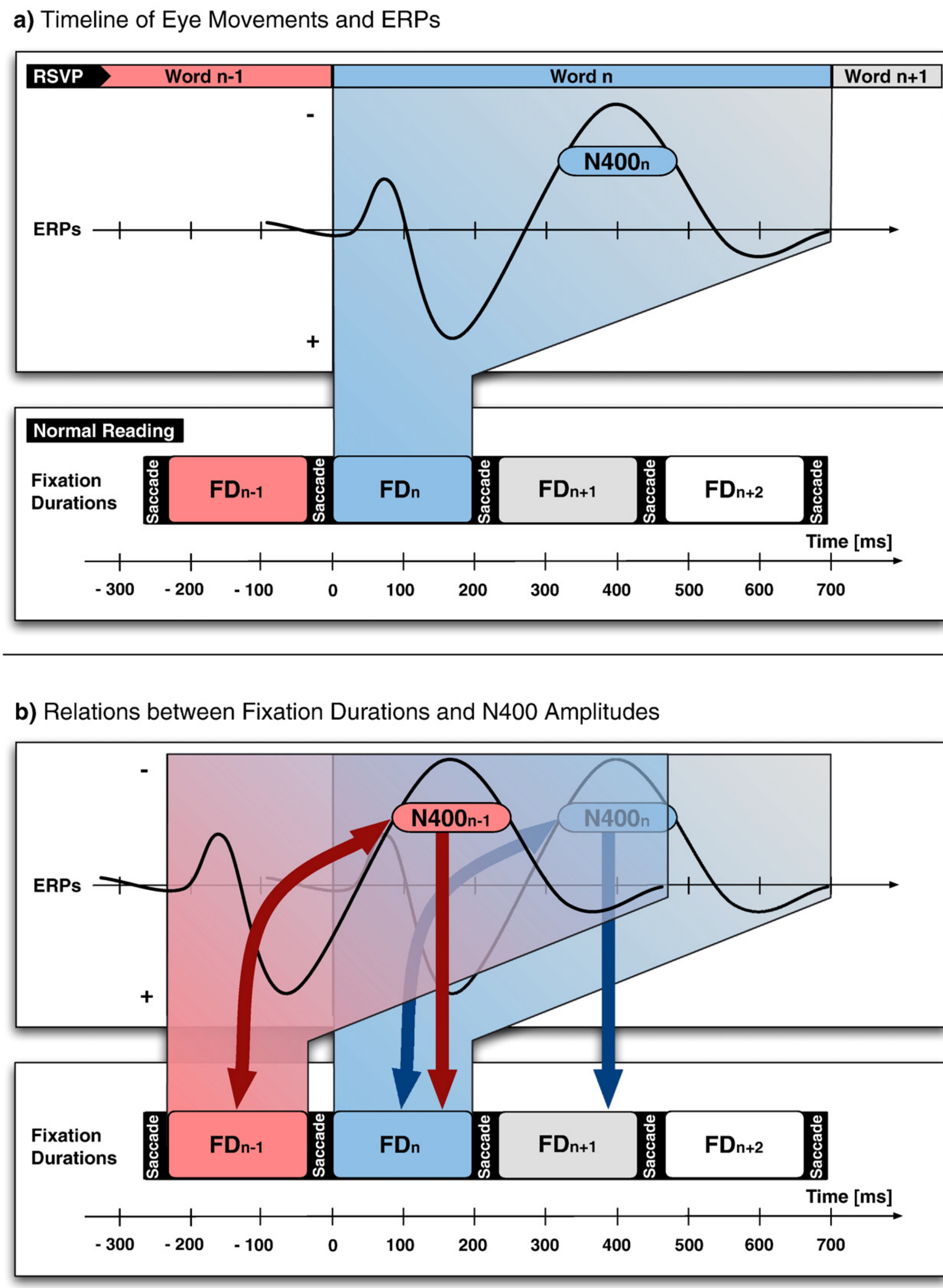

Fig. 4 – Synchronizing the timelines of eye movements and ERPs. Panel a illustrates the time course of fixation durations (FD) during normal reading (bottom) and of ERPs during rapid serial visual presentation (RSVP) of sentences (top). The blue-shaded area denotes that ERP curve and FD_n relate to the same word *n*. Panel b sketches expected relations between FD and N400 amplitudes across different words: correlations (double-headed arrows) between FD and N400 associated with the same word, and uni-directional influence (directional arrow) from N400 on FD on the next word.

(red area). In order to synchronize the two timelines, the ERP course is “shrunk”, so that the stimulus onset in the ERP experiment corresponds to the fixation onset in the eye movement study. Thus, the two ERP curves now overlap substantially. Note that this temporal overlap of components did *not* occur during the ERP experiment. Due to the SOA of 700 ms in the ERP study N400 amplitudes are uniquely attributable to presentation and processing of the corresponding word. Thus, a unique advantage of the combination of RSVP and regular eye movement statistics is that it allows us to unconfound the influence of successive N400 components on successive reading fixations. Arrows in Fig. 4b sketch expected relations between the measures together with the direction of influence. First, we assume a correlation between FD_n and $N400_n$ represented by the blue double-headed curved arrow. The blue straight arrow pointing from $N400_n$ to FD_{n+1} reflects the lag effect: $N400_n$ may influence FD_{n+1}, but not the other way around because

Table 1 – Path-analytic models

	Baseline model			+Immediacy effects			+Lag effects			+Successor effects		
	Coef	SE	*p*	Coef	SE	*p*	Coef	SE	*p*	Coef	SE	*p*
Baseline model												
$FD_{n-1} \leftrightarrow N400_{n-1}$	−4.077	.944	<.001**	−2.068	.771	.007**	−2.068	.771	.007**	−1.861	.758	.014*
$N400_{n-1} \rightarrow FD_n$	−8.900	2.050	<.001**	−7.667	1.827	<.001**	−1.731	1.737	.319	−1.731	1.737	.319
$FD_n \leftrightarrow N400_n$	−4.645	.931	<.001**	−.653	.676	.334	−.752	.601	.211	−.752	.601	.211
$N400_n \rightarrow FD_{n+1}$	−4.242	2.024	.036*	−4.242	2.024	.036*	−2.176	1.996	.276	−2.176	1.996	.276
$FD_{n-1} \rightarrow FD_n$	.040	.052	.449	.065	.048	.171	.008	.043	.859	.008	.043	.859
$FD_n \rightarrow FD_{n+1}$	.166	.051	.001**	.166	.051	.001**	.083	.053	.116	.083	.053	.116
Immediacy Effects												
$f_{n-1} \rightarrow FD_{n-1}$				.725	1.237	.558	.725	1.238	.558	.465	1.229	.705
$f_{n-1} \rightarrow N400_{n-1}$				.053	.029	.066	.053	.029	.066	.057	.029	.047*
$f^2_{n-1} \rightarrow FD_{n-1}$				3.838	.802	<.001**	3.838	.802	<.001**	4.038	.797	<.001**
$f^2_{n-1} \rightarrow N400_{n-1}$				−.082	.019	<.001**	−.082	.019	<.001**	−.085	.019	<.001**
$p_{n-1} \rightarrow FD_{n-1}$				−5.413	1.769	.002**	−5.413	1.769	.002**	−6.077	1.767	.001**
$p_{n-1} \rightarrow N400_{n-1}$				.264	.041	<.001**	.264	.041	<.001**	.275	.041	<.001**
$f_n \rightarrow FD_n$				.992	1.805	.583	−.275	1.622	.865	−.275	1.615	.865
$f_n \rightarrow N400_n$				−.006	.047	.902	−.006	.048	.902	−.006	.047	.902
$f^2_n \rightarrow FD_n$				5.207	1.119	<.001**	4.353	.998	<.001**	4.353	.995	<.001**
$f^2_n \rightarrow N400_n$				−.078	.030	.009**	−.078	.030	.009**	−.078	.030	.009**
$p_n \rightarrow FD_n$				−9.612	1.297	<.001**	−7.103	1.184	<.001**	−7.103	1.184	<.001**
$p_n \rightarrow N400_n$				.269	.035	<.001**	.269	.035	<.001**	.269	.035	<.001**
Lag effects												
$f_{n-1} \rightarrow FD_n$							−7.092	.829	<.001**	−7.092	.829	<.001**
$f^2_{n-1} \rightarrow FD_n$							2.949	.641	<.001**	2.949	.641	<.001**
$f_n \rightarrow FD_{n+1}$							4.966	1.842	.007**	−4.966	1.842	.007**
$f^2_n \rightarrow FD_{n+1}$							1.488	1.216	.221	1.488	1.216	.221
Successor effects												
$p_n \rightarrow FD_{n-1}$										3.895	1.422	.006**
$p_n \rightarrow N400_{n-1}$										−.062	.033	.063
Model statistics												
χ^2	6.4	*df*: 4		150.0	*df*: 22		43.2	*df*: 18		33.5	*df*: 16	
Pr ($>\chi^2$)	.17			<.001			<.001			.006		
RMSEA Index	.042	90% CI: (NA, .10)		.130	90% CI: (.11, .15)		.064	90% CI: (.04, .09)		.057	90% CI: (.03, .08)	
Goodness of Fit Index	.99			.93			.98			.98		
Adj. Goodness of Fit Index	.97			.80			.92			.93		
Bentler–Bonnett NFI	.93			.86			.96			.97		
Tucker Lewis NNFI	.93			.67			.92			.94		
Bentler CFI	.97			.87			.97			.98		
BIC	−17			22			−62			−60		

Path coefficients, standard errors (SE), *p*-values (*$p<.05$; **$p<.01$), and model fit characteristics for four path models. The baseline model denotes relations between fixation durations and N400 amplitudes. In the immediacy, lag and successor effect models, these relations are successively dissolved by the add-on of word frequency and predictability, accounting for the covariation of fixation durations and N400 amplitudes.

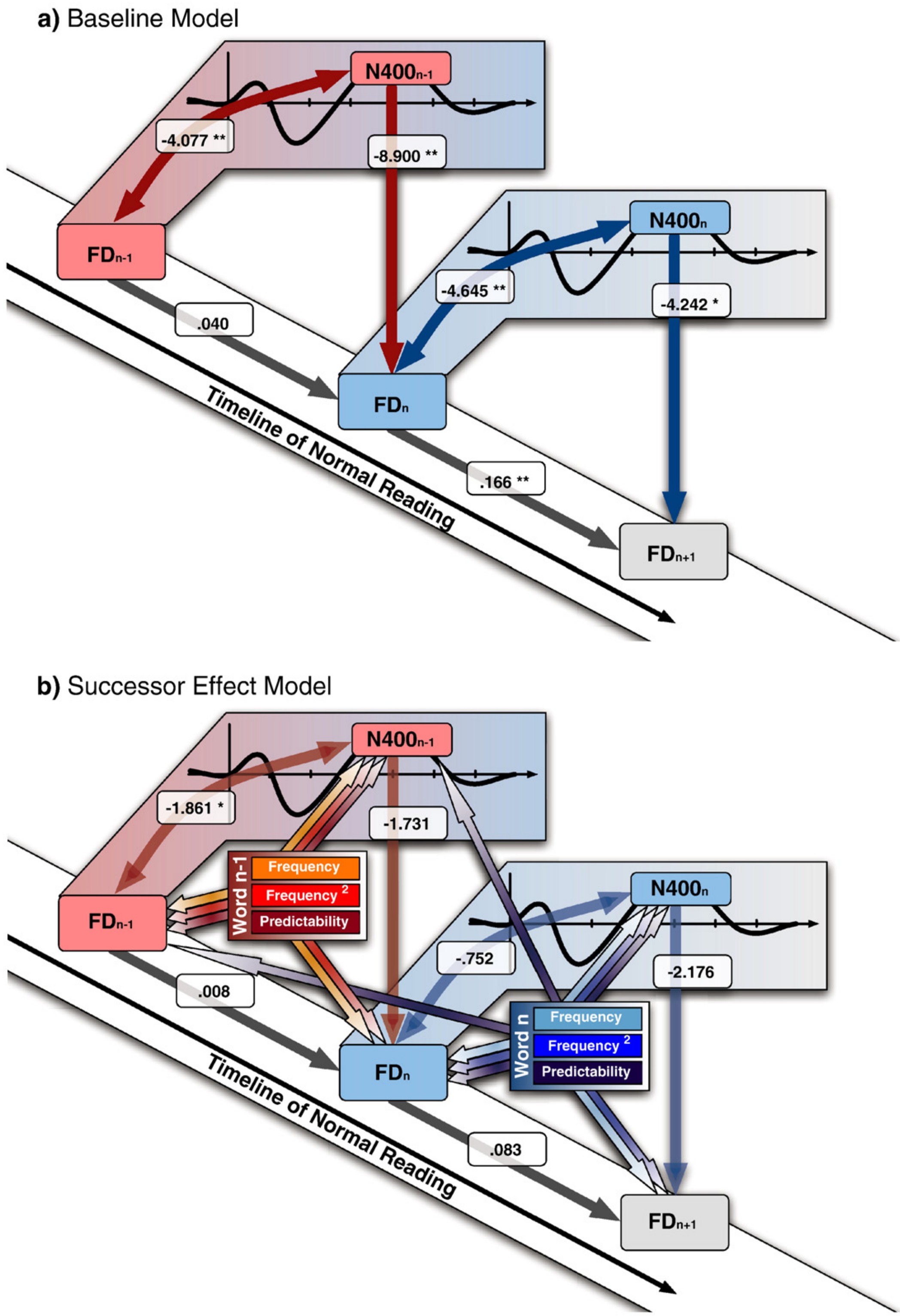

Fig. 5 – Path-analytic models. Visualization of path analyses, together with path coefficients (*$p<.05$; **$p<.01$). Panel a illustrates the baseline model (see also Table 1), i.e., direct relations between N400 amplitudes and fixation durations (FD) across word triplets (word $n-1$, word n, word $n+1$). Panel b shows the successor effect model (see also Table 1) comprising influence of word frequency and predictability in addition to paths in the baseline model.

word $n+1$ in the ERP study was presented only after occurrence of $N400_n$ (i.e., 700 ms after word n). In addition, the same pattern of interrelations is expected for measures relating to word $n-1$ (see red arrows). We predict a co-variance between FD_{n-1} and $N400_{n-1}$ as well as a direct influence from $N400_{n-1}$ on FD_n.

2.3. Baseline path model

The predictions were tested in a path analysis,[3] including also autoregressive paths for fixation durations (i.e., influence from FD_{n-1} on FD_n, and from FD_n on FD_{n+1}). With the simultaneous consideration of relationships between three successive fixation durations together with two corresponding N400 amplitudes we explore reading dynamics in a representative time window. Herein, mutual influence between measures is examined while possible effects of third variables are statistically controlled (e.g., covariance between FD_n and $N400_n$ taking into account influence from $N400_{n-1}$ on FD_n). Moreover, the open-class restriction of word n and class independence of words $n-1$ and $n+1$ grant generalizability across word types.

Path coefficients along with corresponding standard errors and p-values, as well as goodness-of-fit statistics of this *baseline model* are presented in the left part of Table 1 (see also Fig. 5a). Various goodness-of-fit statistics indicate that the specified model is compatible with the observed variance–covariance matrix, e.g., $\chi^2(4)=6.4$, $p=.17$. Thus, the results support the hypotheses outlined above: $N400_{n-1}$ (negative voltages) covaries with FD_{n-1} and $N400_n$ covaries with FD_n. Moreover, both lag effects were significant: the more negative the $N400_{n-1}$, the longer FD_n and the more negative $N400_n$, the longer FD_{n+1}. Finally, there was a positive effect from FD_n on FD_{n+1}, but no influence from FD_{n-1} on FD_n (Table 1: *baseline model*).

Clearly, we established a reliable covariance between eye movement and EEG measures during reading over words. Longer fixation durations go along with larger N400 amplitudes on the corresponding word. Furthermore, neural activity relating to a given stimulus serves as an indicator for fixation durations on the next word. Obviously, language processing is not over once the eyes have left a word but continues while subsequent text is scanned and influences succeeding reading behavior.

2.4. Predictor path models

The reliable covariances suggest that fixation durations and N400 amplitudes are sensitive to a common underlying mechanism, presumably related to word processing. Word frequency and predictability are likely candidates to indicate the common source of this covariance as they are known to affect eye movements as well as ERPs. We tested this hypotheses in three additional path analyses including as exogenous variables *frequency* (f_{n-1}, f_n), *frequency × frequency* (f^2_{n-1}, f^2_n), and *predictability* (p_{n-1}, p_n) of word $n-1$ and of word n, respectively. We expected that, first, these predictors exhibit influences on both fixation durations and N400 amplitudes, as shown in previous research (see Introduction and Figs. 2 and 3). Second, if frequency and predictability are responsible for the common modulation of fixation durations and N400 amplitudes and hence reflect the mediating source, they should absorb covariance of the two measures. Therefore, effects shown in the baseline path model should be no longer significant once frequency and predictability are included in the analysis. Specifically, allowing direct influences on fixation duration and N400 amplitude of corresponding words should cancel the covariance between them, a prediction tested in the *immediacy effect* path analysis (Fig. 6a). Furthermore, we assumed that lag-frequency is responsible for the influence of N400 amplitudes on fixation durations on the next word. This relation should be absorbed, when frequency is coupled to the N400 amplitude of the current word and to fixation duration on the next word. Additionally, we hypothesized that lag-frequency is also responsible for the influence from FD_n to FD_{n+1}. The *lag effect* model examined these hypotheses (Fig. 6b). Finally, the *successor effect* model tested whether predictability of an upcoming word (p_n) accounts for covariance between fixation durations (FD_{n-1}) and N400 amplitudes ($N400_{n-1}$). Such a result would be compatible with readers' online predictions of a not yet visible word (Fig. 6c). Variances, covariances and correlations of the predictors entering the following analyses are shown in Table 2.

In the *immediacy effect model*, frequency and predictability exhibited influence on fixation durations and on N400 amplitudes of the corresponding word. The *baseline model* was expanded by paths from f_{n-1}, f^2_{n-1} and p_{n-1} to FD_{n-1} and $N400_{n-1}$, as well as from f_n, f^2_n and p_n to FD_n and $N400_n$ (see Fig. 6a for a schematic illustration). Table 1 lists path coefficients, standard errors and p-values of this analysis. The covariance between FD_n and $N400_n$ could be set to zero without loss of fit and the covariance between FD_{n-1} and $N400_{n-1}$ was strongly reduced. The latter is expected because the current model does not account for influences from words further back. Coefficients for predictability significantly affected measures on word $n-1$ and word n in the expected direction: fixation durations were longer and N400 amplitudes larger as predictability decreased. Similarly, the quadratic trend of word frequency influenced measures on both words; the linear term of word frequency only revealed a statistical trend for $N400_{n-1}$ (Table 1: *immediacy effect model*). In summary, including frequency and predictability in the path model accounted for the covariance between FD_n and $N400_n$ and largely reduced the covariance between FD_{n-1} and $N400_{n-1}$. Thus, frequency and predictability of words plausibly are a common source for the correlation between eye movement and EEG records.

While the correlation between fixation durations and N400 amplitudes could be traced to the immediate influence of word frequency and predictability on these measures, the lag effect (i.e., the influence of $N400_{n-1}$ on FD_n and of $N400_n$ on FD_{n+1}) was largely unaffected and still significant. In the *lag effect model*, word frequency was set to "spill over", that is to affect fixation durations on the next word. Specifically, connections from f_{n-1} and f^2_{n-1} to FD_n and from f_n and f^2_n to FD_{n+1} were included as predictors in addition to the paths of the *immediacy effect model* (see Fig. 6b for a schematic illustration).[4] The χ^2 statistic suggested a significant improvement in goodness of fit

[3] All path analyses were conducted with the *sem package* (Fox, 2006) implemented in the *R framework*, a language and environment for statistical computing (R-Development-Core-Team, 2006).

[4] Additional analyses revealed that predictability did not account for variance in the lag effect: neither the influence from p_{n-1} on FD_n nor from p_n on FD_{n+1} was significant. Instead, these paths worsened the model fit and were therefore dropped.

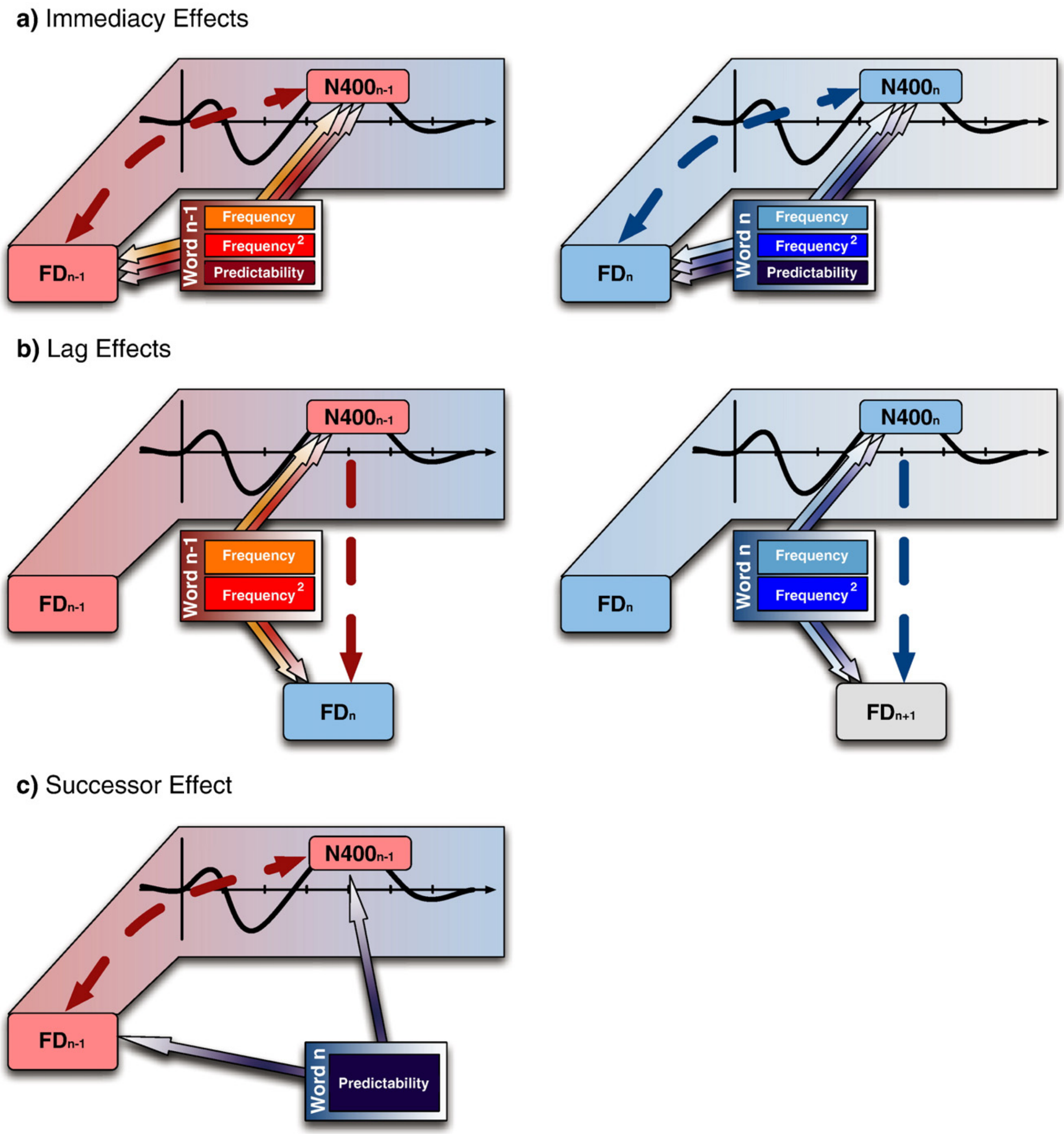

Fig. 6 – Predictor effects. Schematic illustrations of immediacy, lag and successor effects (see also Table 1). Word properties frequency and predictability (solid arrows) exhibit influence on fixation durations (FD) and N400 amplitudes and absorb direct relations between the two measures (dashed arrows). Panel a visualizes how the influence of frequency, frequency^2 and predictability accounts for the correlation between FD and N400 amplitudes associated with the same word (immediacy effects). Panel b shows how frequency explains the influence of N400 amplitude on FD on the next word (lag effects). Panel c sketches how upcoming predictability accounts for common variance between FD and N400 amplitude both relating to a previous word (successor effect).

for the *lag effect model* compared to the *immediacy effect model* ($p<.01$). Importantly, lagged word frequency was sufficient to account for the influence of N400 amplitudes on the succeeding fixation: neither the coefficient from $N400_{n-1}$ to FD_n nor the one from $N400_n$ to FD_{n+1} was reliable any more. Also the influence from FD_n on FD_{n+1} from the baseline model could be left out of the model. Significant path coefficients indicated that fixation duration was shorter, when the previous word was of high frequency. Concerning quadratic lag-frequency, only the path from f^2_{n-1} to FD_n was significant.

Starting from the *baseline model*, all but one of the reliable connections between eye movements and ERPs were explained by frequency and predictability, exhibiting immediate and lagged influence. Only the correlation between FD_{n-1} and

Table 2 – Variance–covariance matrix

	FD_{n-1}	FD_n	FD_{n+1}	$N400_{n-1}$	$N400_n$	f_{n-1}	f^2_{n-1}	p_{n-1}	f_n	f^2_n	p_n
FD_{n-1}	664.87	55.88	−72.54	−4.08	.63	−3.46	9.96	−3.82	−3.60	.75	1.96
FD_n	.08	672.08	130.70	−3.91	−4.53	−16.70	12.03	−7.40	−8.46	15.64	−10.65
FD_{n+1}	−.12	.21	594.50	−.22	−2.58	1.31	4.94	1.82	−7.82	11.37	−4.49
$N400_{n-1}$	−.24	−.23	−.01	.43	−.01	.32	−.20	.28	.02	−.03	.03
$N400_n$	.04	−.27	−.16	−.02	.43	.06	−.03	.03	.17	−.29	.28
f_{n-1}	−.10	−.47	.04	.36	.07	1.89	−.12	.81	−.01	−.11	.27
f^2_{n-1}	.23	.27	.12	−.18	−.02	−.05	2.86	.17	−.31	.33	−.13
p_{n-1}	−.15	−.30	.08	.43	.04	.61	.10	.93	.00	−.03	.20
f_n	−.14	−.32	−.32	.03	.26	−.01	−.18	.00	1.01	−1.17	.31
f^2_n	.02	.39	.30	−.02	−.28	−.05	.13	−.02	−.74	2.45	−.39
p_n	.08	−.43	−.19	.04	.44	.20	−.08	.22	.32	−.26	.92

Variances (diagonal), covariances (above diagonal) and correlations (below diagonal) of fixation durations (FD), N400 amplitudes (N400) and word properties [frequency (f), frequency×frequency (f^2) and predictability (p)], relating to words $n-1$, n and $n+1$ (indicated by subscripts).

$N400_{n-1}$ remained significant. In a final path model we examined, whether this covariance could be ascribed to predictability of the upcoming word. Compared to the *lag effect model*, additional paths in this *successor effect model* defined influence from p_n on FD_{n-1} and $N400_{n-1}$ (Table 1; Figs. 5b and 6c). χ^2 statistics confirmed an improved fit for this successor effect model compared to the lag effect model ($p<.01$). Including p_n reduced but did not eliminate the correlation between FD_{n-1} and $N400_{n-1}$. Thus, predictability accounted for common variance of fixation duration and N400 amplitudes of the previous word. The significant path from p_n to FD_{n-1} uncovered that fixation durations are longer when the next word is of high predictability. The path from p_n to $N400_{n-1}$ revealed a trend indicating that N400 amplitudes are larger as well, when they are succeeded by a high-predictable word. Finally, compared to the previous models, the influence of f_{n-1} on $N400_{n-1}$ was enhanced, as indicated by a significant coefficient.

2.5. *Model fit*

In the path models including frequency and predictability as exogenous variables, χ^2 statistics were significant, indicating that the observed variance–covariance matrix was not recovered with the model equations. It is well known, however, that for large sample sizes (as in the present data), the χ^2 statistic tends to reject otherwise acceptable models. The *lag* and *successor effect models* meet the conventional acceptability criteria of derived statistics that "correct" this shortcoming (Table 1). For instance, root mean square error of approximation (RMSEA) corrects statistics for sample size and model complexity; a model is considered reasonable when RMSEA is below .08 (Loehlin, 2004; Schlösser et al., 2006). Values larger than .90 for various other fit indices lead to the same conclusion.

Model fitting was also strongly guided by theoretical considerations. Starting with a core set of predictors we improved the model by including additional predictors in a stepwise manner. The most parsimonious model (*immediacy effect model*) had a considerably poorer fit than the final ones (*lag and successor effect models*), as reflected for example in the substantially lower value of the Bayes–Schwartz Information Criterion (BIC, see Table 1). In this context, the primary purpose of the present path analyses was to trace relations between eye movements and ERPs to a common source. Therefore, we restricted our analyses to theoretically motivated links that might serve as a common source for the observed relations between fixation durations and N400 amplitudes. Word frequency and predictability lived up the expectation of being plausible candidates. The third candidate, word length, explained variance in only one of the measures (i.e., fixation durations) and was left out of the analyses for reasons of model parsimony.[5]

3. Discussion

The comparison of eye movement and ERP data from two independent reading studies (i.e., Kliegl et al., 2006 and Dambacher et al., 2006, respectively) utilizing the same sentence material suggested strong relations between fixation durations and N400 amplitudes (Figs. 2 and 3). After synchronizing timelines of fixation durations from normal reading and N400 amplitudes from word-wise sentence presentation, the *baseline model* established the interdependence of these measures with words as units of analysis. In a second set of analyses, *immediacy*, *lag* and *successor effects* were traced to the common influence of frequency and predictability in three successive path analyses. We will discuss the findings separately in the following section.

The *baseline model* revealed a correlation between fixation durations and N400 amplitudes, both relating to the same word. Longer fixation durations were associated with larger N400 amplitudes. In the *immediacy effect model*, frequency and predictability were identified as sources of this common modulation as the inclusion of these variables accounted for the covariance between FD_n and $N400_n$ and reduced substantially the correlation between FD_{n-1} and $N400_{n-1}$. The fact that the latter was still significant presumably points to influences from words further back, which were not taken into consideration in the present analyses. This explanation predicts also other relations, e.g., an influence from p_{n-1} to $N400_n$ that was not significant. This could simply be due to insufficient statistical power. It may also mean that our explanation is not sufficient.

[5] Word length did not affect N400 amplitudes of the present data set (Dambacher et al., 2006).

In summary, the immediacy effect model demonstrated that frequency and predictability effects are similarly reflected in two different measures of word recognition: fixation durations and N400 amplitudes are sensitive to lexical and post-lexical variables. This reveals that both measures are influenced by at least one common stage of word recognition, on which frequency as bottom–up and predictability as top–down variables act together. Given that fixation durations are strongly related to lexical processing, the correspondence between the two measures suggests that N400 amplitudes reflect online lexical processing as well, which is at odds with a purely post-lexical interpretation (e.g., Brown and Hagoort, 1993).

Another result points to a lexical role of the N400. Its peak latency at around 400 ms and its sensitivity to lexical and post-lexical variables denote that word processing is not completed after a fixation of 200 or 250 ms, but unfolds even when the visual information is no longer accessible. The temporal overlap of N400 amplitudes and fixation durations on the next word suggested a relation between the two measures across word boundaries. Considering eye movement studies showing that fixation durations increase, when the previous word was of low frequency (Kliegl et al., 2006; Schroyens et al., 1999), we tested whether the temporal coincidence of ERPs and eye movements accounts for this lag effect. We examined the influence of N400 amplitudes on fixation durations on the consecutive word in the *baseline model*. Indeed, larger N400 amplitudes entailed longer fixation durations. In the *lag effect model*, this relation was traced to the influence of word frequency: low-frequency words elicited larger N400 amplitudes and, at the same time, caused longer fixation durations on the next word. The coherence of N400 amplitudes and longer subsequent fixation durations provides a neurophysiological correlate for the lag effect during reading with frequency as mediating source.

A possible reason for this result is reduced efficiency of word recognition during the processing of low-frequency words. While lexical access of high-frequency words happens fast and automatically within the first 200 ms post-stimulus, identification of low-frequency words is much slower and ranges into the N400 time window (Dambacher et al., 2006). Thereby, large N400 amplitudes arise at a time when the eyes during normal reading usually fixate the next word. This temporal coincidence may cause interference, such that increased N400 activity reduces resources of word recognition and therefore inhibits lexical processing of a fixated word. Consequently, lexical access of a stimulus following a low-frequency word is delayed and fixation durations are prolonged.

A second interpretation is even more in line with the cognitive lag hypothesis assuming that lexical processing continues after saccade execution (Bouma and de Voogd, 1974; Kolers, 1976). Kolers proposed that eye movements are triggered largely independently from word recognition, but that the cognitive system can intervene when necessary. The present results can be construed in terms of this approach: concerning eye movements, the word recognition system estimates the additional time necessary to complete word processing when a low-frequency word is encountered. Accordingly, saccade execution is inhibited and therefore a fixation is prolonged. However, due to the relative slowness of cognitive processes, the inhibition arises with a delay; the increase of inspection time happens to occur only during the next fixation, which presumably is on the next word (e.g., Engbert et al., 2005, for an implementation of this proposal in a computational model of saccade generation during reading). In ERPs, the N400 is known as a sensitive measure for the difficulty of word processing. Also strength of saccade inhibition – or additional fixation time – is presumably calculated on the basis of word difficulty. Thus, it is reasonable to assume that saccade inhibition is to some degree proportional to N400 amplitudes. When saccade inhibition arises during the next fixation, due to temporal delay, inspection time on this word is proportional to the N400 amplitude on the previous stimulus.

The present evidence for the lag effect holds important implications for models of eye movement control in reading. Model architecture has to permit fixation durations to be influenced by properties of a previously fixated word. A mechanism similar to the cognitive lag hypothesis is implemented in SWIFT, a model based on parallel word processing (Engbert et al., 2002; Engbert et al., 2005). In SWIFT, an autonomous timer initiates saccades after a randomly chosen interval. When a difficult word is encountered, the lexical processing system is able to inhibit the saccade generator, which entails an increase of fixation duration. However, because the cortical word recognition processes are much slower than the fast brainstem saccade generator, this inhibition process is delayed (e.g., tau = 375.7 ms, Engbert et al., 2005) and potentially arises only during the next fixation. In that case, inspection durations following the critical fixation on a difficult word are prolonged. In contrast, E-Z Reader (Reichle et al., 1998; Reichle et al., 2003), a serial attention-shift model of eye movement control, accounts for spillover effects in terms of reduced parafoveal preview rather than in terms of ongoing processing: when word n has been accessed, attention is immediately shifted to word $n+1$, while saccade execution, which is partially independent from attentional shift, usually occurs later. Thus, fast processing of word n grants more time to process word $n+1$ parafoveally. Under special situations it is also possible in E-Z Reader that word $n+1$ is fixated before word n is lexically accessed. However, such “premature saccades” are unlikely and would often result in a regression back to the word that is being processed (Pollatsek et al., 2006). Instead, lexical access even of difficult words is usually completed, before a saccade is executed (see also Fig. 4 in Reichle et al., 2003); consequently, for E-Z Reader spillover due to incomplete processing is presumably not a determinant critically influencing reading behavior. Evidence for lag effects due to ongoing lexical processing of previous words challenges the plausibility of this implementation on a neurophysiological level.

In the final analysis, we addressed the potential influence of an upcoming word on fixation durations and N400 amplitudes. In eye movement research, there is some controversy whether lexical or – if at all – only sublexical information can be extracted from a parafoveal, not yet fixated stimulus during normal reading (Kennedy and Pynte, 2005; Rayner et al., 2003; Vitu et al., 2004). We will not enter this debate here because parafoveal view was not possible in the present ERP experiment as sentences were displayed word-by-word. Thus, parafoveal preview cannot be responsible for common modulation of the two measures, neither for successor nor for lag effects (in terms of E-Z Reader). Nonetheless, in the *successor* *effect model*, predictability accounted for covariance of fixation durations and N400 amplitudes on the previous word. For eye movements, Kliegl et al. (2006) had already reported successor effects with longer fixation durations, when the subsequent word was of high predictability. They proposed that the high-predictable word could be retrieved from memory without being fixated and that therefore inspection durations on the previous word increased. In the ERP data, also N400 amplitudes tended to be larger when they preceded a high-predictable word; note that N400 amplitudes *following* a high-predictable word usually are smaller. This suggests that participants made predictions about the upcoming stimulus, which was reflected in additional neural activity on the previous word. Strong predictions could be made, whenever contextual constraint was high, whereas it was hardly possible to predict the upcoming word in a low constraining context. Considering that the SOA of 700 ms in the present ERP experiment provides unnaturally much time, this effect might even be stronger than in normal reading situations. Admittedly, this interpretation is speculative and needs to be confirmed in further experiments since the influence of predictability on the previous N400 amplitude only revealed a trend. There is some support for this interpretation from reports of N400 effects on the word before a critical stimulus. DeLong et al. (2005) varied predictability of nouns, half of them starting with a vowel and half of them with a consonant. The nouns were embedded in word-wise presented sentences and were preceded by the phonologically correct article *an* or *a*, respectively. N400 amplitudes measured on the article were (inversely) correlated with the predictability of the subsequent noun; they were larger, when the article *an* was presented, while a consonant-initial noun was expected, and vice versa. Similarly, articles or adjectives, whose gender mismatches the expected succeeding noun, evoked larger N400 or P600 amplitudes (Van Berkum et al., 2005; Wicha et al., 2003a,b, 2004). These results, together with the present findings, reveal that readers make online predictions about the identity of an upcoming stimulus, even in the absence of parafoveal visual information, and that these predictions are reflected in fixation durations as well as in ERPs (Kliegl et al., 2006; Kutas et al., 2006).

The present approach of comparing eye movements and ERPs from independent experiments has been used in previous studies. For example, Raney and Rayner (1993) examined changes in eye movements and ERPs, when small text passages were read for the second time. They concluded that re-reading affects multiple lower- and higher-level determinants reflected in both measures. Sereno et al. (1998) collected eye movement data during normal reading using 288 target words embedded into single-line sentences. ERPs were measured employing the same target words together with 192 nonwords in a lexical decision task. The authors proposed a timeline for word recognition on the basis of their results. However, the usage of different stimuli (Raney, 1993; Raney and Rayner, 1995) or different tasks (Sereno et al., 1998) eventually reduces the comparability of the data. As far as we know, the present paper is the first to relate fixation durations and N400 amplitudes from experiments with identical stimuli and tasks to each other and therefore provides optimal data comparability.

Of course, one difference is still that eye movements are recorded in normal reading situations, while sentences in ERP settings are presented word-wise with long intervals between stimuli. Critical researchers doubt that data assessed with this procedure reflect normal reading processes (for a discussion see e.g., Rayner, 1998). This assumption, however, is premise not only for the validity of our conclusions, but also for the generalizability of numerous previous experiments utilizing RSVP paradigms. Although some reports suggest good correspondence between results of RSVP and more natural settings (Hagoort and Brown, 2000a,b; Kutas et al., 1988; Van Berkum, 2004), this issue has to be explicitly addressed in the future. For instance, SOAs in RSVP experiments should be approximated to natural reading rate of four or five words per second. On the one hand, this would prevent ERP data from being contaminated by eye movements and variable fixation onsets. Nevertheless, researchers would have to face the problem of component overlap — unless they do not limit their analyses to sentence-final words, where sentence wrap-up effects reduce generalizability. Very careful selection and strict control of the stimulus material could override this problem. On the other hand, shortening of SOAs would provide evidence, whether word recognition differs at various reading rates. In fact, some studies indicate that SOA manipulation affects language-related ERPs (Hagoort and Brown, 2000a; Van Petten, 1995; Van Petten and Kutas, 1987).

Another straightforward way to examine the soundness of RSVP results and particularly to compare fixation durations and ERPs directly is simultaneous recording of eye movements and EEG signals during normal sentence reading. Both measures are then collected from a subject within the same experiment in one setting. Despite various methodological and technical problems, attempts on this innovative method are promising (Dimigen et al., 2006).

3.1. *Conclusions*

We jointly analyzed eye movements and ERPs and found that fixation durations and N400 amplitudes during sentence reading substantially relate to each other. Both measures are modulated by the same word properties and therefore are presumably influenced by common processes of word recognition. The present paper demonstrates how different methods of psycholinguistic research can be combined and thereby incorporates advantages of both measures. We are confident that future research will strongly benefit from cross-linking eye movements and ERPs.

4. Experimental procedures

Detailed methods on acquisition of eye movement as well as EEG data are published elsewhere (see Kliegl et al., 2006; Dambacher et al., 2006, respectively).

4.1. *Stimuli*

The Potsdam Sentence Corpus (PSC) served as stimulus set in the eye movement and the ERP study. The PSC comprises 144

German sentences (1138 words) with a large variety of grammatical structures. Mean sentence length is 7.9 words with a range from 5 to 11 words. Values for frequency [based on *Das Digitale Wörterbuch der deutschen Sprache des 20. Jahrhunderts* (http://www.dwds.de, 2006; Geyken, in press, in preparation)] and predictability [collected in an independent cloze task (see Kliegl et al., 2004)] were available for all corpus words, along with other independent variables such as word length and ordinal position of the word in the sentence.

4.2. Eye movements

4.2.1. Participants

Eye movement data were collected from 125 German speakers (16 to 56 years) with normal or corrected-to-normal vision. They were paid or received study credit at the University of Potsdam.

4.2.2. Procedure

Participants (seated 60 cm from the screen; head positioned on a chin rest) were instructed to read the sentences for comprehension. After validation of the accuracy of a standard nine-point grid calibration, a fixation spot appeared in the center-line on the left side of the monitor. If the eye-tracker detected a valid fixation on the spot, a sentence was presented so that the midpoint between the beginning and the center of the first word was positioned at the location of the fixation spot. Sentences (font: New Courier 12; visual angle: 0.35° per letter) were shown until participants looked to the lower right corner of the screen. An extra calibration was carried out if the tracker did not detect the eye at the initial fixation point within 2 s.

4.2.3. Recording and data processing

Eye movements were recorded with EyeLink I and II systems (SR Research, Osgoode, ON, Canada) with sampling rates of 250 Hz and 500 Hz, respectively, and an eye position resolution of 20 arc sec. Calibrated eye position was recorded accurately at the level of letters. Data were collected in two laboratories with identical equipment and setup.

Eye movement data were screened for loss of measurement and blinks. Data of sentences without problems were reduced to a fixation format after detecting saccades as rapid binocular eye movements (Engbert and Kliegl, 2003). Only single fixations (i.e., words exactly fixated once) with durations between 50 ms and 750 ms entered analyses. Finally the first word of each sentence was removed. This screening resulted in a total of 42,847 data points.

4.3. ERPs

4.3.1. Participants

Fifty subjects (19 to 35 years; 43 right-handed) were paid for participation at the Catholic University of Eichstätt-Ingolstadt. All were native German speakers and had normal or corrected-to-normal vision.

4.3.2. Procedure

Participants were positioned 60 cm from the monitor and were instructed to read the sentences for comprehension. A fixation-cross indicated the position of the first word on the screen. A sentence was then presented word by word (font: New Courier 12). Each stimulus together with the adjacent punctuation was displayed for 250 ms and a stimulus onset asynchrony (SOA) of 700 ms in black on a white screen (Rapid Serial Visual Presentation; RSVP). Sentence order was randomized.

4.3.3. Recording and data processing

EEG data were collected with an electrode cap (ElectroCap International) on 26 locations corresponding to the revised 10/20 International System. Amplified voltages (0.1–100 Hz; sampling rate: 256 Hz) originally referenced to one electrode on the left mastoid were converted offline to average reference. Two horizontal and two vertical EOG electrodes recorded bipolarly eye movements and blinks. Impedances of scalp electrodes were kept below 5 kΩ.

Data of two subjects had to be excluded from further processing, one because of data loss and one because of a former neurological disease. Due to artifact contamination, a total of 11.43% of the data from the remaining 48 subjects were eliminated. The continuous EEG recording was divided into 800 ms epochs beginning 100 ms before stimulus onset. Data were baseline-corrected relative to a 100 ms pre-stimulus interval.

4.4. Data reduction

In the EEG data, we identified the N400 component in the time window from 300 to 500 ms over centro-occipital electrodes (CZ, C3, C4, CP5, CP6, PZ, P3, P4, P7, P8, O1, O2) as in the study of Dambacher et al. (2006). They chose this epoch and these channels for N400 analyses after visual inspection and in accordance with previous reports (cf. Kutas et al., 2006). N400 amplitudes were computed by collapsing voltages across selected electrodes, across sampling points in the 200 ms interval and across subjects. Thus, we obtained one average N400 amplitude for each corpus word. For analyses we specified N400 amplitudes of the currently presented word n ($N400_n$) together with N400 amplitudes of the previous word $n-1$ ($N400_{n-1}$).

Likewise, fixation durations were collapsed across participants resulting in one average single-fixation duration for each word in the PSC. In addition to the fixation duration associated with a currently fixated word n (FD_n) we also

Table 3 – Word statistics

	Open-class words			Closed-class words		
	n	Mean	SD	*n*	Mean	SD
Word n−1						
Frequency	209	1.52	.98	134	3.66	.72
Predictability	209	−2.10	.72	134	−1.11	.99
Word n						
Frequency	343	1.54	1.00			
Predictability	343	−1.77	.96			
Word n + 1						
Frequency	154	1.61	1.06	189	3.64	.65
Predictability	154	−1.87	.85	189	−.70	1.09

Descriptive statistics for words $n-1$, n and $n+1$: number of open- and closed-class words together with mean and standard deviation (SD) of word frequency and predictability.

determined the fixation duration on the preceding word $n-1$ (FD_{n-1}) and on the succeeding word $n+1$ (FD_{n+1}).

In the ERP as well as in the eye movement data set, word n was restricted to the category of open-class words (e.g., nouns, verbs). Closed-class words (e.g., determiners, pronouns) were excluded. Note that this selection criterion did not pertain to word $n-1$ or word $n+1$: while FD_n as well as $N400_n$ were derived from open-class words, FD_{n-1}, $N400_{n-1}$, and FD_{n+1} could correspond to either open-class or closed-class words. Moreover, sentence-initial and sentence-final words were excluded. We also made sure that neither FD_{n-1} nor $N400_{n-1}$ stemmed from the sentence-initial word, and likewise that FD_{n+1} was not from sentence-final position. Therefore, word n varied between the third position from the beginning and the third word from the end of a sentence. The data reduction resulted in a total of 343 open-class words n each comprising a unique value for $N400_{n-1}$, $N400_n$, FD_{n-1}, FD_n and FD_{n+1} (see Table 3 for word statistics).

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