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Research Report

Model-generated lexical activity predicts graded ERP amplitudes in lexical decision

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ABSTRACT

Recent neurocognitive studies of visual word recognition provide information about neuronal networks correlated with processes involved in lexical access and their time course (e.g., [Holcomb, Ph.J., Grainger J. and O'Rourke, T. (2002). An Electrophysiological Study of the Effects of Orthographic Neighborhood Size on Printed Word Perception, J. of Cogn. Neurosci. 14 938–950; Binder, J.R., McKiernan, K.A., Parsons, M.E., Westbury, C.F., Possing, E.T., Kaufman, J.N. and Buchanan, L. (2003). Neural Correlates of Lexical Access during Visual Word Recognition, J. Cogn. Neurosci. 15 372–393]). These studies relate the orthographic neighborhood density of letter strings to the amount of global lexical activity in the brain, generated by a hypothetical mental lexicon as speculated in an early paper by [Jacobs, A.M. and Carr, T.H. (1995). Mind mappers and cognitive modelers: Toward cross-fertilization, Behav. Brain. Sci. 18 362–363]. The present study uses model-generated stimuli theoretically eliciting graded global lexical activity and relates this activity to activation of lexical processing networks using event-related potentials (ERPs). The results from a lexical decision task provide evidence for an effect of lexicality around 350 ms post-stimulus and also a graded effect of global lexical activity for nonwords around 500 ms post-stimulus. The data are interpreted as reflecting two different decision processes: an identification process based on local lexical activity underlying the 'yes' response to words and a temporal deadline process underlying the 'no' response to nonwords based on global lexical activity.

1. Introduction

Studies of visual word recognition focusing on lexical access employ a number of variables assumed to influence this process (e.g., word frequency or neighborhood density) in a number of tasks (e.g., lexical or semantic decision, naming, or perceptual identification). One of the most prominent variables is neighborhood density, i.e., the number of orthographic neighbors, which can be generated by changing one letter of a given word, often referred to as the N-metric (Coltheart et al., 1977). When participants make a lexical decision, a standard finding is that responses to words of large neighborhoods (so called high-N words) are faster than to words having small neighborhoods (Andrews, 1989, 1992, 1997; Carreiras et al.,

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1997; Forster and Shen, 1996; Grainger and Jacobs, 1996; Sears et al., 1995). On the other hand, reaction times to nonwords are slower when these stimuli have many word neighbors. Grainger and Jacobs (1996) offered an explanation for this dissociation. According to their multiple read-out model of word recognition (MROM), either of two decision criteria is in effect when subjects make decisions in the lexical decision task. The standard criterion is based on the individual word representation in memory which is activated by a presented word, triggering a positive 'yes' response for this specific item. The second criterion is based on a measure of global lexical activity representing the summed activity in the mental lexicon.

If subjects rely on the second criterion, based on global lexical activity, it is assumed that words with large number of neighbors generate increased global lexical activation in a hypothetical mental lexicon through the partial activation of all representations in memory. This extra activity could be used to make faster 'yes' responses compared to words with small number of neighbors generating lower levels of global lexical activity.

According to Grainger and Jacobs (1996), the measure of global lexical activity could also explain the inhibitory effects for 'no' responses to nonwords with a large number of neighbors. In the case of 'no' decisions to nonwords, the MROM has implemented a temporal deadline mechanism based on the summed lexical activity in the lexicon. It is assumed that nonwords with large number of neighbors generate also high levels of global lexical activity through the activation of word neighbor representations. This high global lexical activity prolongs the variable deadline and therefore results in slower correct 'no' responses to nonwords with large number of neighbors.

Therefore, it is possible that the opposite effects for words and nonwords having large number of neighbors in reaction times are based on the same global activity levels yielding faster responses to words and slower responses to nonwords but are based on different response criteria (Coltheart et al., 2001; Forster and Shen, 1996; Grainger and Jacobs, 1996).

Two recent neurocognitive studies investigated this hypothesis. Both studies relate the hypothetical global lexical activity elicited by words and nonwords of different neighborhood density to brain activity. Binder et al. (2003), using measures of blood–oxygen level-dependent (BOLD) responses to letter strings in a functional magnetic resonance imaging (fMRI) study, argued: "If neighborhood density is correlated with activation of lexical representations, and if activation of these representations is associated with neural activity, then it is reasonable to expect differences in brain activation for stimuli with large compared to small neighborhoods, regardless of whether the stimuli are words or nonwords". Unexpectedly, Binder et al. were not able to confirm this prediction and concluded that BOLD responses were not related to processing at a presemantic "word code" level.

The predictions of the ERP study of Holcomb et al. (2002) point in the same direction: "We argued that the same core mechanism, operating on global lexical activity, is at the basis of both the facilitatory and the inhibitory effects of orthographic neighborhood density on behavioral responses to word and nonword stimuli in the lexical decision task". It was then argued that a measure of processing that directly reflects variations in global lexical activation should show effects of neighborhood density that are in the same direction for word and nonword stimuli. In contrast to Binder et al. (2003), Holcomb et al. found effects of neighborhood density in lexical and semantic decision, which revealed differences in N400 amplitudes for both words and nonwords with high-N, confirming their predictions.

Both studies more or less directly tested predictions of interactive activation models of word recognition (Grainger and Jacobs, 1996; Jacobs and Grainger, 1992; Johnson and Pugh, 1994; McClelland and Rumelhart, 1981). Thus, while currently available neuroimaging evidence concerning the effects of orthographic neighborhood density does not support predictions of localist connectionist models of word recognition, the evidence from an ERP study does so. However, both studies mentioned above tested predictions of computational models indirectly and in a dichotomous way. They used the N-metric (Coltheart et al., 1977) to operationalize the global lexical activity generated by letter strings in simulation models such as the MROM or the revised dual-route cascaded (DRC) model (Coltheart et al., 2001) and 2 × 2 designs with stimuli of either small or large neighborhoods. In the present study, we

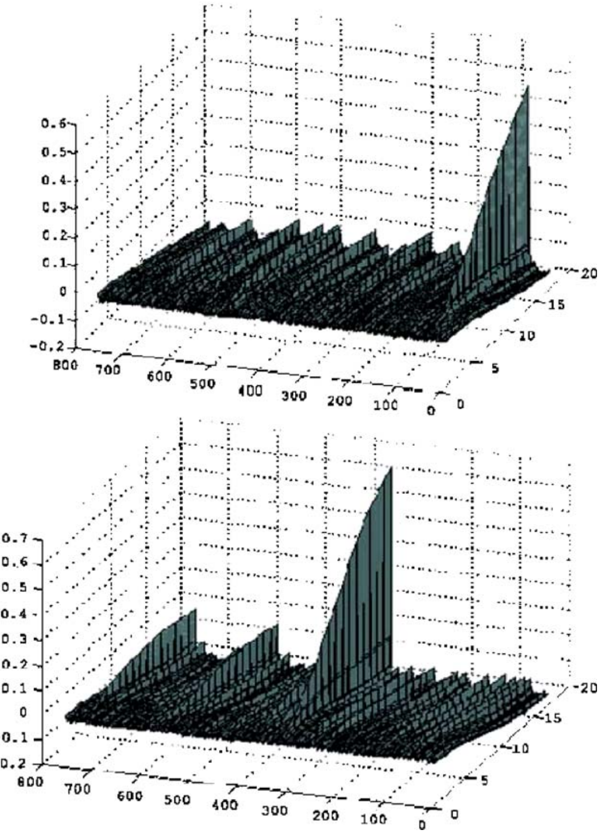

Fig. 1 – 3D plots of the hypothetical global lexical activation generated by two stimuli in the MROM, the nonword BFXZ (upper panel) and the word KIND (i.e., child; lower panel). The vertical (*z*) axis gives model activation values, the horizontal (*x*) axis gives a section of the extent of the lexicon (entries 1 to *n*), and the depth (*y*) axis gives cycle time.

attempted to go a step further by using graded, model-generated activity levels for words and nonwords. The idea was to directly determine the hypothetical amount of lexical activity generated by these letter strings and to examine to what extent behavioral and ERP parameters correlate with these variations of simulated global lexical activity levels.

In order to generate stimuli for the ERP study, we used the MROM as described in Grainger and Jacobs (1996) and, more recently, in Jacobs et al. (2003) using a lexicon of 1025 monosyllabic three-to-five letter German words. All 551 four-letter words were chosen from the CELEX database (Baayen et al., 1993), and a pool of 2000 nonwords was generated from these words by changing one, two, three, or four letters, excluding combinations that formed words. All stimuli were then submitted to the MROM to determine the overall lexical activity generated by each stimulus. As a stable measure of this overall lexical activity, the average summed lexical activation across the first seven cycles of processing was computed and transformed into z values. 300 words and 300 nonwords were then selected so that the two resulting distributions were normal with significantly different means and equal variances. Further, the 600 stimuli were then divided into six groups according to their level of global lexical activation for purposes of analyses of variance (ANOVA; for stimulus characteristics see Appendix). Fig. 1 shows the simulated global lexical activation for two stimuli in the MROM.[1]

The main aim of this study was to test the prediction of the MROM according to which 'no' responses in the lexical decision task systematically depend on the global lexical activation of the nonwords, as recently suggested by Holcomb et al. (2002). If global lexical activity is correlated with brain activity, we should observe a systematic graded variation of the ERP, in particular of the N400 amplitude in response to nonwords (see Roesler and Hahne, 1992 for an overview of the language specificity of the N400). The case of words is less clear. Recent behavioral and computational data obtained in a data-limited variant of the lexical decision task showed that under such error-producing conditions, words are often correctly classified on the basis of a fast-guess, signal detection mechanism that uses global lexical activation as information (Jacobs et al., 2003).

In contrast, under the implemented presentation duration of 100 ms, a nearly optimal exposure condition, this fast-guess mechanism should hardly operate (Jacobs et al., 2003). For such conditions, the MROM predicts that 'yes' responses are based on a high-threshold, lexical identification mechanism, which is sensitive to word and neighborhood frequency rather than to neighborhood density, i.e., to local lexical (i.e., single detector) activation rather than to global lexical activation (Grainger and Jacobs, 1996). We therefore expected that global lexical activation has little or no effect on ERPs to words in the current study.[2]

2. Results

2.1. *Behavioral data*

Nonwords_1 yielded the shortest 'no' reaction times and lowest error rates followed by nonwords of group two and three (nonwords_2, nonwords_3). For words, the pattern was reversed those having the lowest global lexical activation levels (words_1) yielded the slowest 'yes' reaction times and highest error rates followed by words with medium and high levels of global lexical activity (words_2 and words_3) see Table 1.

The repeated measures ANOVA for reaction times revealed effects of lexicality and a significant interaction of lexicality and global lexical activity, but no main effect of global lexical activity. Lexicality: $F(1,22) = 93.54$, $P < 0.001$, MSE = 609,882.11, global lexical activity: $F(1,22) = 2.36$, $P = 0.11$, MSE = 1400.22, lexicality by global lexical activation: $F(2,44) = 87.66$, $P < 0.001$, MSE = 38,651.54.

Individual repeated measures ANOVAs for reaction times for global lexical activity performed separately for words and nonwords reached significance: $F(2,44) = 41.35$, $P < 0.001$, MSE = 12,822.21, and $F(2,44) = 38.03$, $P < 0.001$, MSE = 26,863.56, respectively.

The repeated measures ANOVA for error rates revealed a significant interaction of lexicality and global lexical activity, but no main effects: lexicality: $F(1,22) < 1$, $P = 0.97$, MSE = 0.18, global lexical activity: $F(1,22) < 1$, $P = 0.72$, MSE = 3.51, lexicality by global lexical activity: $F(2,44) = 34.45$, $P < 0.001$, MSE = 675.48.

Individual repeated measures ANOVAs for error rates for global lexical activity performed separately for words and nonwords reached significance: $F(2,44) = 19.07$, $P < 0.001$,

Table 1 – Behavioral data

GLA	RT			Errors		
	N	Mean	SD	Mean	SD	%
Nonwords_1	23	758.08	106.47	6.39	5.42	9.11
Nonwords_2	23	791.32	98.62	8.52	5.95	11.39
Nonwords_3	23	825.79	102.65	13.00	8.87	16.11
Words_1	23	680.58	81.47	12.52	6.73	13.89
Words_2	23	661.71	77.87	9.39	5.30	11.04
Words_3	23	634.03	75.38	5.78	4.27	6.86

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[1] Concerning the model-generated graded stimuli and their theoretical global lexical activation, a recent study by Graf et al. (2005) using (partial) correlation analysis with 551 four-letter German words of the CELEX database provides information on the factors that could determine global lexical activity in the model. Graf et al. found a variety of variables that affect global lexical activity significantly. The most important ones were: number of neighbors ($R^2 = 0.75$; $P < 0.001$), bigram frequency (type, i.e., the number of bigrams shared with other words; $R^2 = 0.58$; $P < 0.001$), number of higher frequency neighbors ($R^2 = 0.32$, $P < 0.001$), number of positions of higher frequency neighbors ($R^2 = 0.18$; $P < 0.001$), and log word frequency ($R^2 = 0.05$, $P < 0.001$). This analysis shows that while it may often be reasonable to estimate global lexical activity via the N-metric, other factors that may not have been controlled, such as higher frequency neighbors, might have played an important role in determining the results.

[2] The results of Holcomb et al.'s lexical decision experiment showed a significant neighborhood density effect on N400 amplitude to words, but also a stronger neighborhood density effect for nonwords than for words.

MSE = 323.45, and $F(2,44) = 22.2$, $P < 0.001$, MSE = 377.24, respectively.

All pairwise comparisons for reaction times and error rates performed separately for words and nonwords for the levels of global lexical activity reached significance: RT: nonwords_1 vs. nonwords_2: $t(22) = -4.55$, $P < 0.001$, nonwords_1 vs. nonwords_3: $t(22) = -8.23$, $P < 0.001$, nonwords_2 vs. nonwords_3: $t(22) = -4.46$, $P < 0.001$, words: words_1 vs. words_2: $t(22) = 3.7$, $P = 0.001$, words_1 vs. words_3: $t(22) = 9.55$, $P < 0.001$, words_2 vs. words_3: $t(22) = 5.1$, $P < 0.001$.

Error rates: nonwords_1 vs. nonwords_2: $t(22) = -3.23$, $P = 0.004$, nonwords_1 vs. nonwords_3: $t(22) = -5.2$, $P < 0.001$, nonwords_2 vs. nonwords_3: $t(22) = -4.43$, $P < 0.001$, words: words_1 vs. words_2: $t(22) = 2.38$, $P = 0.03$, words_1 vs. words_3: $t(22) = 6.35$, $P < 0.001$, words_2 vs. words_3: $t(22) = 4.24$, $P < 0.001$.

The mean confidence ratings revealed that participants were very sure of both their word and nonword decisions: for nonwords, mean ratings varied from 1.6 for nonwords_1 to 1.7 (nonwords_2), and 1.95 for nonwords_3; for words, the values were 5.3 (words_1), 5.3 (words_2) and 5.4 (words_3). Thus, the results of the confidence ratings are in line with the error analysis.

The correlation analysis for global lexical activity and other linguistic measures with reaction time yielded significant correlations for words and nonwords. For words, reaction times were affected by LOGF: $r = -0.44$; $P < 0.001$, GLA: $r = -0.20$; $P < 0.001$, N: $r = -0.11$, $P = 0.03$, BIC: $r = -0.13$, $P = 0.02$, and BIN: $r = -0.10$, $P = 0.049$. For nonwords, N: $r = 0.46$; $P < 0.001$, HFN: $r = 0.41$; $P < 0.001$), GLA: $r = 0.37$; $P < 0.001$, BIC: $r = 0.42$, $P < 0.001$, and also BIN: $r = 0.27$; $P < 0.001$ were correlated with reaction time. Thus, the correlation analysis revealed effects of global lexical activity for both words and nonwords.

2.2. *ERP data*

22.8% of the trials were rejected because of artifacts. The ERP morphology starts with a first negative deflection occurring between 100 and 150 ms from stimulus onset (N1). This was followed by a positive deflection occurring at approximately 200 ms (P2). A significant negativity followed the P2, with a peak around 350 ms. After a short positive deflection, a later significant negativity appeared with a peak around 500 ms (N400). Fig. 2 shows the grand average of all participants for the effect of lexicality and nine selected electrode positions.

There was an early main effect of lexicality ranging from 300 ms to 390 ms: $F(1,23) = 32.06$, $P < 0.001$, MSE = 64.42, with nonwords generating greater negativity than words. Global lexical activity levels produced no effect in this time window: $F(2,44) = 1.08$, $P = 0.35$, MSE = 1. There was no significant lexicality by global lexical activation interaction: $F(1,23) = 2.82$, $P = 0.07$, MSE = 1.69.

The second negative component in the time window from 450 ms to 550 ms revealed main effects of lexicality: $F(1,22) = 46.19$, $P < 0.001$, MSE = 169.69 and global lexical activity: $F(2,44) = 14.91$, $P < 0.001$, MSE = 35.43, but no significant interaction: $F(2,44) = 3.42$, $P = 0.06$, MSE = 5.05. Additionally performed pairwise comparisons revealed significant effects for the global lexical activity levels for nonwords: nonwords_1 vs. nonwords_2: $t(22) = 4.64$, $P < 0.001$, nonwords_1 vs. nonwords_3: $t(22) = 6.18$, $P < 0.001$, nonwords_2 vs. nonwords_3: $t(22) = 3.61$, $P = 0.002$, but not for words: words_1 vs. words_2: $t(22) = 1.03$, $P = 0.32$, words_1 vs. words_3: $t(22) = 1.83$, $P = 0.08$, words_2 vs. words_3: $t(22) = 1.67$, $P = 0.11$. Fig. 3 shows the grand average of all participants for the effect of global lexical activity and nine selected electrode positions.

3. Discussion

The current study was designed as a test of two predictions of the MROM. The MROM predicts that 'no' responses to nonwords in the lexical decision task should systematically depend on global lexical activation. According to the MROM, under near optimal exposure conditions 'yes' responses should be based on a high-threshold lexical identification mechanism. Therefore, global lexical activity should have no or little effect on ERPs to words.

The behavioral analysis revealed that nonwords with the lowest level of global lexical activity yielded the fastest reaction times and nonwords with high levels of global lexical activity yielded the slowest reaction times. For words, the response pattern was reversed. Thus, the behavioral analysis confirmed the predictions of the MROM that reaction times to nonwords were influenced by their different levels of global lexical activity. In contrast to the predictions of the MROM, the behavioral analysis revealed also effects of global lexical activity for words.

The ERP analysis revealed a significant negativity between 300 and 390 ms post-stimulus reflecting the word-nonword difference and a later negativity between 450 and 550 ms post-stimulus that reflects the global lexical activation level of nonwords, but not of words. We thus have an early categorical lexicality effect with nonwords eliciting a larger negativity than words, and later, parametric effect of global lexical activation for nonwords, but not for words. Thus, the lexical status of the stimulus had an impact on ERPs before and possibly independently of their corresponding global lexical activation level.

Given that reaction times to words were about 130 ms faster than to nonwords, we propose that the second component (N400) reflects the operation of a temporal deadline mechanism for nonwords, as assumed by the MROM. In the MROM, 'no' responses to nonwords are computed on the basis of global lexical activation levels. The graded N400 effect therefore could reflect processing differences for nonwords of different global lexical activation levels with nonwords having high global activation levels requiring more computation compared to nonwords having low global lexical activity levels. We think that nonwords at least partially activate orthographic and phonologically similar words as well as their word neighbors and probably semantic information associated with these words. Words in the mental lexicon should be activated stronger the more word-like the nonwords are. This leads to higher activity in the mental lexicon making a no decision for these nonwords more difficult. Therefore, the deadline for no decisions for those nonwords is prolonged. This was also supported by the results of the correlation analysis which showed that global lexical

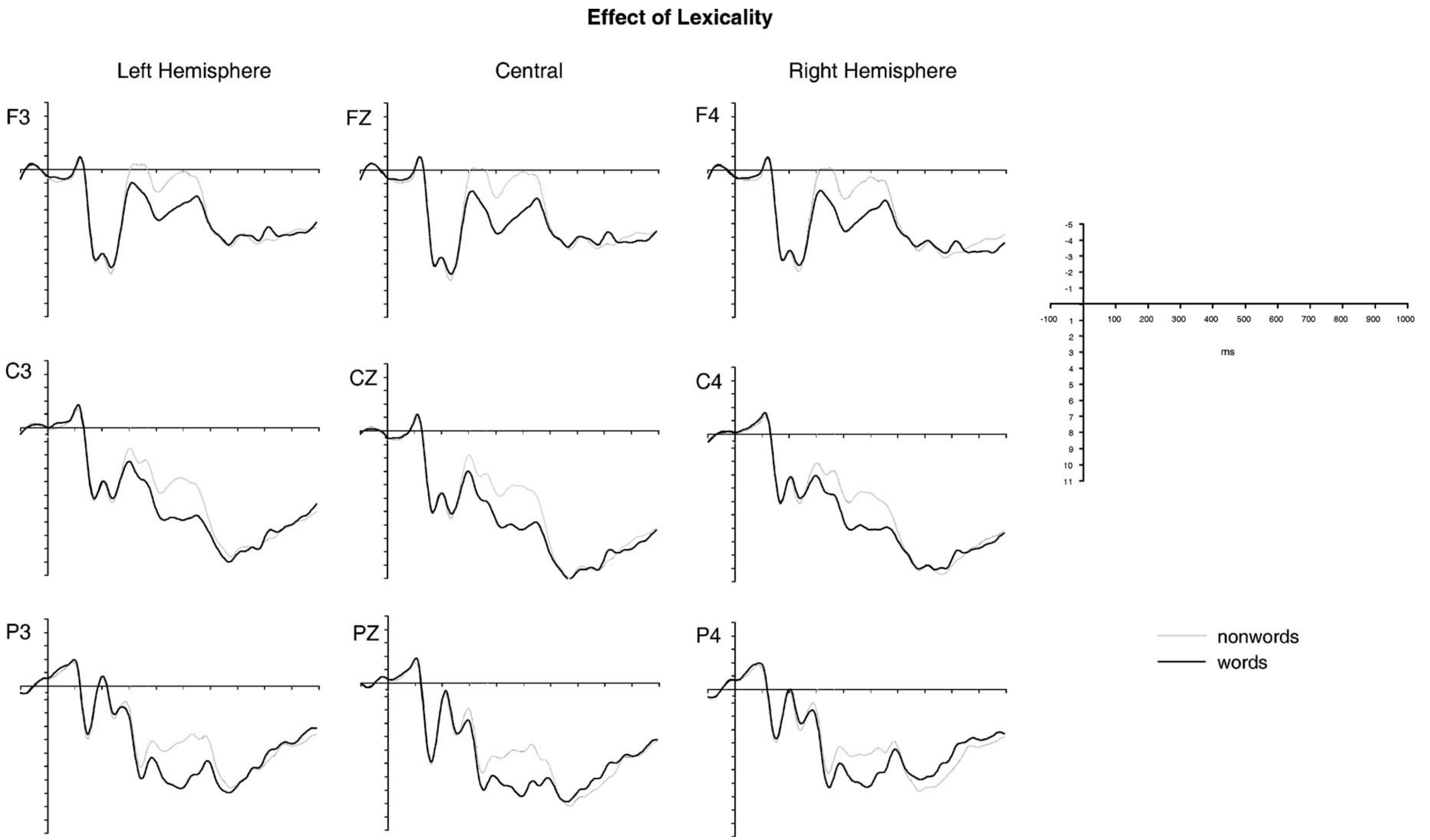

Fig. 2 – Grand averages for words and nonwords of all participants from selected scalp positions. Plotted in this figure are the grand averages from 23 participants for word and nonword stimuli. Words are represented by the black solid line and nonwords by the grey solid line. Note that stimulus onset is represented by the vertical microvolt calibration bar and that negative voltages are plotted in the upward direction.

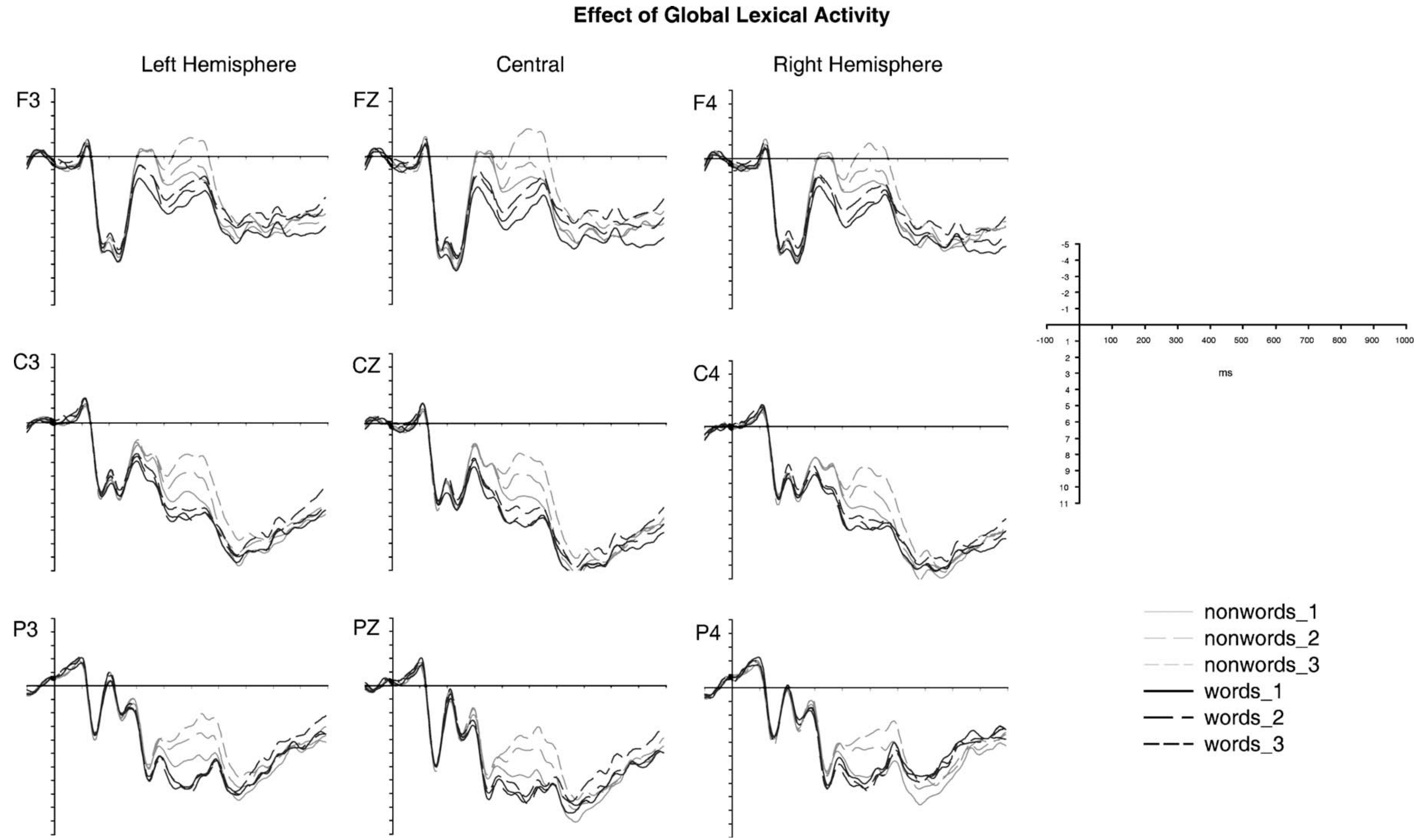

Fig. 3 – Plotted in this figure are the grand averages for the levels of global lexical activity from selected scalp positions from 23 participants. Nonword groups are represented by the following lines: nonwords_1 (most word unlike) = ——, nonwords_2 = — —, nonwords_3 = - - -. Word groups are represented by the following lines: words_1 = —— (most word unlike) = words_2 = — —, and group six words_3 = – – – .

activity and also neighborhood density are correlated with reaction times for nonwords.

The interpretation in terms of a temporal deadline mechanism is supported by a second result of our study that was not observed by Holcomb et al. (2002) and that is also important with regard to the key assumptions underlying computational models such as the MROM or the DRC. The second result is the categorical effect of lexicality on ERPs in the 300 to 390 ms time window. We think that this component reflects the threshold identification process assumed by the MROM because the effect is independent of the global lexical activation level of both words and nonwords.

Together with the behavioral evidence (i.e., the clear categorical response sureness ratings), the absence of any modulation of this effect by global lexical activation suggests that under the present conditions a fast-guess mechanism was not involved in the computation of 'yes' responses: any significant involvement would predict graded effects of global lexical activation on ERPs. Using 100 ms presentation durations presumably suffices for allowing successful lexical access and for lexical or semantic information to become available for driving the 'yes' response. Thus, we interpret this lexicality effect, peaking at 350 ms, as the electrophysiological signature of 'yes' decisions, possibly based on a discrete (i.e., high-threshold) identification process.

Relating the observed lexicality effect at 350 ms post-stimulus to the time course of visual word recognition, we propose that this is the point in time when lexical access was about to happen in our study. Previous studies revealed similar effects of lexicality (e.g., Carreiras et al., 2005; Hutzler et al., 2004; McKinnon et al., 2003). These studies also found larger negativities for nonwords compared to words starting at 300 ms. However, most of the studies used word frequency to indicate the point in time when lexical access happens. The effects of word frequency and lexicality are mainly located in the same time range from 300 to 500 ms (e.g., Barber et al., 2004; Brown et al., 1999; Johannes et al., 1996; Rugg, 1990; Van Petten and Kutas, 1990), but see (Assadollahi and Pulvermueller, 2001a; Hauk and Pulvermüller, 2004; Pulvermueller et al., 1995; Sereno et al., 1998) for evidence of earlier lexical access.

The effects for nonwords on the N400 corroborate and extend those of Holcomb et al. (2002), who already showed that greater global lexical activity of nonwords as estimated by the N-metric lead to greater N400 amplitudes. Compared to Holcomb et al., in this study, a direct parametric (three levels) output of a computational model of visual word recognition was used as an estimate of the summed activity in the mental lexicon.

Concerning the dissociation found in reaction times between words and nonwords (fast responses to words and slower responses to nonwords with many neighbors), it was hypothesized by Grainger and Jacobs (1996) that this dissociation is based on the same mechanism of global lexical activity which should be reflected in the brain's activity. This was confirmed by Holcomb et al. In contrast to Holcomb et al., we did not observe an effect of global lexical activity (i.e., the summed activity of the mental lexicon) for words on the N400 component. An effect of global lexical activity for words was only found in reaction times. One possible explanation for this result could be found in the specifics of global lexical activity (i.e., words of high frequency also had a large number of orthographic neighbors).

Holcomb et al. (2002) showed that words with a large number of neighbors produced higher negative ERP amplitudes compared to those with a small number of neighbors. In contrast, ERP amplitudes in response to words of high frequency are less negative compared to low frequency words (e.g., Barber et al., 2004; Hauk and Pulvermüller, 2004; Johannes et al., 1996; Rugg, 1990). In their study, Holcomb et al. controlled their neighborhood stimuli for frequency using words of relatively low frequency (Mean = eight per million). In our study, higher levels of global lexical activity resulted in higher word frequency and also higher neighborhood density. Furthermore, we used words of relatively high frequency (Mean = 109 per million). Therefore, it is possible that the measure of global lexical activity comprises the effects of frequency and neighborhood density for words. This is confirmed by the results of the correlation analysis for reaction times, where word frequency and neighborhood density are negatively correlated with reaction times resulting in fast behavioral responses for words, but probably prevent a graded effect of global lexical activity for words in the ERP.

We are aware of the fact that our interpretations are speculative given that they more directly connect the output from a computational model to behavioral and electrophysiological data than is usually found in the literature. On the other hand, we thus take the challenge expressed by Jacobs and Carr (1995) more seriously than an increasing number of word recognition studies in the cognitive neurosciences that uses computational models of word recognition such as the MROM or DRC to interpret ERP or fMRI data in a more indirect way, that is, verbally, without actually using simulations to predict the data.

4. Experimental procedures

4.1. *Participants*

Twenty-eight right-handed students of the University of Leipzig (Germany) participated in the study. All were native German speakers and were paid for their participation. All had normal or corrected to normal vision. Mean age was 23 (range: 19 to 30 years); 11 participants were male.

4.2. *Experimental materials and procedure*

Nonwords were divided into three groups of 100 stimuli with the following indices of mean global lexical activation: nonwords_1 = 0.16 (e.g., KNBE) nonwords_2 = 0.21 (e.g., BOFT), and nonwords_3 = 0.26 (e.g., KAND). Words were also divided into three groups of 100 stimuli according to their mean global lexical activation: words_1 = 0.20 (e.g., KLON-clone), words_2 = 0.25 (e.g., KLUG-smart), and words_3 = 0.30 (e.g., KIND-child).

To further characterize the processing of letter strings in visual word recognition, the following variables were chosen for a later correlation analysis: global lexical activity (GLA), word frequency per million (FMIO), log word frequency (LOGF), neighborhood density (N), summed frequency of neighbors (FN), number of higher frequency neighbors (HFN), summed frequency of the higher frequent neighbors (FHFN) and bigram count (BIC; the number of times the bigrams of a given word/nonword appears in other words), bigram frequency (BIF; the summed frequency of words which contain the given bigram), and bigram neighbors (BIN; number of words which differ only in one bigram).

An IBM compatible computer was used for stimulus presentation and response measurement. All stimuli were four letters long and presented in black upper case letters (4.1*1 cm high) on a light-grey screen. At a viewing distance of 70 cm, the stimuli subtended a visual angle of approximately 0.82°. Stimuli were presented in Courier type font on a 17″ color monitor (resolution 1024 × 768 pixels, 75 Hz).

Stimulus presentation and response recording were controlled by ERTS software (BeriSoft Corp., Germany). Stimuli were presented in six pseudo-randomized blocks of 100 trials with the restriction that no more than three stimuli of one type followed each other. Participants were instructed to perform the lexical decision task as fast and as accurate as possible. Each trial consisted of a fixation point (:), shown for 400 ms, followed by the stimulus for 100 ms. Participants had to press the left button of a response pad with their left thumb, and the right button with the right thumb, the response-hands were counterbalanced across participants. Immediately after the stimulus, a mask (+++++) appeared until a response was given, but no longer than four seconds. At the end of each trial, participants were asked to rate the confidence of their response using a six-point scale, i.e. from 6 = "sure a word", over 5 = "less sure a word", to 1 = "sure a nonword". Participants were allowed to make a short break after each block of 100 trials.

Participants were given 10 s to indicate their degree of confidence in their decision by clicking with the mouse on one of six response fields. The participants' response terminated the trial and the next trial was initiated 1000 ms after the participants button press. Each participant completed 30 practice trials before the start of the experiment. The practice stimuli consisted of 15 words and 15 nonwords taken from the same pool as the experimental stimuli.

4.3. *ERP measurement*

The EEG was recorded on an IBM compatible computer running on Linux OS and ANT Software (ANT Software, NL). All analyses were done using EEProbe from ANT Software. After participants took place in a comfortable chair in an acoustically shielded chamber, the EEG was recorded with an elastic cap (Easy Cap Corp., Germany), using 25 electrodes following the standard international 10–20 system referenced to left mastoid (FP1, FP2, F3, F4, F7, F8, FZ, FC3, FC4, FT7, FT8, CZ, C3, C4, T7, T8, PZ, P3, P4, CP5, CP6, P7, P8, O1, O2). The vertical EOG was recorded from electrodes placed over and below the right eye. The horizontal EOG was recorded from positions at the outer canthus of each eye.

Impedances for scalp and mastoid electrodes were less then 5 kΩ, eye electrodes below 20 kΩ. The biosignals were amplified low-pass with 30 Hz and digitized with 250 Hz continuously throughout the experiment. The 25 active sites were interfaced to a Neuroscan (Neuroscan Inc., TX, USA) amplifier system. All analyses were performed off-line after the experimental session.

4.4. *Data analysis*

Participants with error rates more than 17% were excluded from the analysis. No items were excluded from the analysis because of high error rates. Furthermore, responses with reaction times below 200 ms and above 2000 ms were excluded.

For all stimuli and participants mean reaction time, standard deviation and percentage of errors were calculated. Trials with artifacts, such as muscle artifacts, eye movements and amplifier blocking were rejected by visual inspection; peaks that exceeded ±40 μV were automatically rejected. Single-participant averages were calculated for each of the six conditions, followed by a grand average in a time window from 100 ms before until 1000 ms after stimulus-onset. Two negative peaks, the expected N400 and a negative component around 350 ms post-stimulus, were interesting for the present analyses. Mean amplitudes were measured in relation to a baseline of 100 ms before stimulus onset. Repeated measures ANOVAs were performed on mean voltage data within the following two latency windows: 300 to 390 ms and 450 to 550 ms. The Geisser–Greenhouse correction (Geisser and Greenhouse, 1959) was applied to all repeated measures containing more than one degree of freedom in the numerator.

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Appendix A. Characteristics of the six stimulus groups

GLA	LOGF	FMIO1	N	FN	BIC	BIF
Words_1	2.35	50.46	1.62	62.20	23.78	2231.02
Words_2	2.52	91.13	3.35	239.39	35.35	4442.91
Words_3	3.83	186.78	6.67	1383.58	48.64	9973.79
Nonwords_1	–	–	1.73	146.09	18.06	2130.37
Nonwords_2	–	–	3.45	374.84	31.46	3189.49
Nonwords_3	–	–	5.66	770.90	41.24	6238.52

Note. GLA = global lexical activity level, LOGF = logarithm to the base 10 (total word frequency/million), FMIO1 = total word frequency/million, *N* = number of orthographic neighbors, FN = summed frequency of orthographic neighbors, BIC = the number of times the bigrams of a given word/nonword appears in other words, BIF = the summed frequency of words which contain the given bigram.

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