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Orthographic and Associative Neighborhood Density Effects: What is Shared, What is Different?

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Abstract

Words with many orthographic neighbors elicit a larger N400 than words with few orthographic neighbors. This has been interpreted as stronger overall semantic activation due to orthographic neighbors activating their semantic representations. To investigate this claim, we manipulated the number of associates of words (NoA), a variable directly affecting overall semantic activation, and compared this to the ERP effect of the number of orthographic neighbors (N) in a lexical decision task. Words with high NoA and with high N produced a very similar increase of the N400. In addition, a higher N increased the amplitude of the Late Positive Complex. The common N400 effect suggests that N affects semantic activation, like NoA does. The late positive effect specific to N could occur because words with few orthographic neighbors initially elicit little activity in the orthographic system, thereby resembling nonwords, which leads to distinct processing.

Descriptors: visual word recognition, semantic representation, association, orthographic neighbors, language, ERP

Orthographic and Associative Neighborhood Density Effects: What is Shared, What is Different?

The recognition of written words entails the activation of various levels of representation, from a visual-perceptual level, via orthographic and phonological levels, to the semantic level. A wide-spread assumption in theories of visual word recognition is that the presentation of a given word does not activate only the representations of that particular word, but also those of similar words (e.g., Bowers, Davis, & Hanley, 2005).

For the orthographic level this is borne out in the idea of an orthographic neighborhood. Coltheart, Davelaar, Jonasson, and Besner (1977) defined an orthographic neighbor as a word that can be derived from another word by changing one letter in a specific position, keeping the number of letters constant – in other words, orthographic neighbors are words that are identical except for one letter. The word *cat*, for example, has the orthographic neighbors *bat, rat, cut, cap, car,* etc. When reading the word *cat*, its orthographic neighbors are assumed to be activated also to some degree because of their extensive overlap in letters in each position [1]. Coltheart's N, also referred to as orthographic neighborhood density, indicates for a given word how many orthographic neighbors it has. A wide range of studies has shown that orthographic neighborhood density influences visual word recognition (for a review see Andrews, 1997). The majority of studies using lexical decision has found a facilitatory effect of orthographic neighborhood density: responses to words with a high N (i.e., many orthographic neighbors) are faster and more accurate than to words with a low N (e.g., Andrews, 1989, 1992, 1997; Carreiras, Perea & Grainger, 1997; Pollatsek, Perea & Binder, 1999; see Siakaluk, Sears & Lupker, 2002, for a review). This is a well-established effect that has been replicated in different languages and with various populations, including novel readers and dyslexic readers (e.g., Duñabeitia & Vidal-Abarca, 2008; Lavidor, Johnston & Snowling, 2006; Laxon, Coltheart & Keating, 1988).

The effect of neighborhood density is often explained in terms of an interactive activation model where a written word activates matching letter units and those letter units in turn activate word units containing these letters, with activation also flowing back from the word to the letter units (McClelland & Rumelhart, 1981). In such a framework, the presentation of a particular word would not only activate the word unit corresponding to that word but also the word units of its orthographic neighbors, due to the extensive orthographic overlap. As a consequence, words with many orthographic neighbors would lead to the activation of more word units than words with few orthographic neighbors. Furthermore, activation from orthographic word units would flow back to letter units and back again to word units, leading to a further build-up in overall lexical activation. Grainger and Jacobs (1996) proposed that this might actually be the basis of the facilitatory effect in lexical decision, by way of a task-specific strategy. In their Multiple Read-Out Model (MROM) two mechanisms are available that can lead to a “word” response. The first is unique identification and corresponds to a specific word unit reaching a certain activation threshold. Once a particular word is identified the participant gives a “word” response. The second mechanism is a fast familiarity-based guess as to whether a stimulus is an actual word, as suggested by Balota and Chumbley (1984). Within the framework of the interactive activation model, this is operationalized through overall lexical activation: If a stimulus generates a large amount of (unspecific) lexical activation then a good guess would be that the stimulus is word-like, granting a “word” response. As words with many orthographic neighbors would activate many word units and thus generate high overall lexical activation, this could be the basis for high-N words showing faster RTs than low-N words in lexical decision.

An interesting question is whether orthographic neighbors might also activate their corresponding semantic representations. This could be expected in the spirit of an interactive activation or feed-forward model of visual word recognition. A study with event-related potentials (ERPs) by Holcomb, Grainger, and O'Rourke (2002) actually seems to indicate that orthographic neighbors activate their semantic representations. Holcomb et al. presented high- and low-N words to the participants in their study and found that the ERP showed a bigger N400 for high- than for low-N words. The N400 is a component that responds to a series of semantic manipulations, like semantically incongruent words in sentences, cloze probability, and semantic priming (for a review see Kutas & Van Petten, 1994). Based on such findings, researchers have argued that the N400 reflects the activation of semantic representations in long-term memory (Kutas & Federmeier, 2000) or, alternatively, the integration of semantic information in a post-lexical stage (Brown & Hagoort, 1993; Holcomb, 1993). Interestingly, the N400 also reacts to manipulations that are not per se semantic and might be assumed to rather affect pre-semantic lexical stages, like lexical frequency and phonological priming. Thus, the effects of both lower-level and semantic factors seem to converge on the process underlying the N400. This is consistent with a semantic locus of the N400 as in the proposals cited above, given the assumption that activation can spread from lexical to semantic representations in a feed-forward manner. Given this view of the N400, Holcomb et al. proposed that the N400 effect of orthographic neighborhood density reflected overall semantic activation, even though the underlying manipulation is orthographic in nature: The activation of orthographic neighbors on the lexical-orthographic level would lead to the activation of the respective semantic representations and consequently produce an N400 effect proportional to the number of orthographic neighbors. They argued that the general semantic interpretation of the N400 outlined above would be suggestive of this proposal, although they admittedly could not exclude that the effect might be entirely orthographic in nature.

Several behavioral studies actually found evidence that orthographic neighbors activate their respective semantic representations (Boot & Pecher, 2008; Duñabeitia, Carreiras, & Perea, 2008; Pecher, Zeelenberg, & Wagenmakers, 2005; Rodd, 2004). Duñabeitia, Carreiras et al. (2008), for example, found evidence that words activate their ortho-phonological neighbors up to the semantic level in a study of ortho-phonologically mediated associative priming. They used Spanish prime-target pairs like *oveja – MIEL* (sheep - HONEY), with the prime being preceded by a forward mask and presented for only 50 msec, being immediately replaced by the target. *Oveja* is an ortho-phonological neighbor of *abeja* (bee) in Spanish, which in turn is an associate of *MIEL*. In a lexical decision task, participants responded significantly more rapidly when such ortho-phonological neighbors of associates preceded target words than when unrelated control words did so. It is noteworthy that this ortho-phonologically mediated associative priming effect was very similar in size to the direct associative priming effect, that is, the effect for associated prime-target pairs such as *abeja – MIEL*, as obtained in the same study.

Behavioral studies providing evidence for the semantic activation of orthographic neighbors show that a semantic origin of the N400 effect of orthographic neighborhood density is a definite possibility. A more direct test of the claim that this N400 effect is semantic in nature would be to compare it with a manipulation assumed to involve the semantic level of representation, such as a manipulation involving the number of semantic associates. This is one of the aims of the current study. In the following we first give some background on semantic activation in visual word recognition and then detail the semantic manipulation which we will compare to the orthographic neighborhood density effect.

Various studies have investigated the potential influence of semantics on visual word recognition, manipulating variables such as the number of semantic features (Pexman, Holyk, & Monfils, 2003; Pexman, Lupker, & Hino, 2002; Pexman, Hargreaves, Siakaluk, Bodner, & Pope, 2008), the diversity of contexts in which a certain word occurs (Adelman, Brown, & Quesada, 2006; McDonald & Shillcock, 2001; Pexman et al., 2008), and the number of semantic neighbors in a high-dimensional semantic space derived from co-occurrences in large text corpora (Buchanan, Westbury, & Burgess, 2001; Pexman et al., 2008). A very promising measure proposed to reflect semantic richness is the number of associates (NoA) a word has – which is the measure we will focus on in this study. NoA is defined as the number of different first associates produced in a free association norming study, where participants are presented with a particular word and asked to note down the first word that comes to their mind. This variable has a long tradition in memory research and it has been shown that words with few associates lead to better performance in cued recall than words with many associates (e.g., Nelson, Schreiber, & McEvoy, 1992). It has recently also found its way into research on visual word recognition: Buchanan et al. (2001) found that words with a high NoA produced faster lexical decision times than words with a low NoA, although this effect depended on the interaction with another semantic variable derived from the Hyperspace Analog to Language (HAL) model (Lund & Burgess, 1996). Subsequent studies provided further evidence that high-NoA words result in faster lexical decision times than low-NoA words (Balota, Cortese, Sergent-Marshall, Spieler, & Yap, 2004; Duñabeitia, Avilés, & Carreiras, 2008; Locker, Simpson, & Yates, 2003; Mirman & Magnuson, 2008; Yates, Locker, & Simpson, 2003). For instance, Mirman and Magnuson (2008) investigated the influence of various potential measures of semantic richness on lexical decision. Partial correlations indicated that NoA was as good a predictor of lexical decision performance as measures based on semantic feature norms and co-occurrence based measures.

The findings from memory and psycholinguistic research regarding NoA have been interpreted as evidence that the presentation of a particular word leads to the activation of its associates. Thus, NoA is conceived as associative neighborhood density, with words having many associates as inhabiting a dense associative neighborhood and words having few associates as inhabiting a sparse associative neighborhood. Regarding the different direction of the effects of NoA on cued recall and lexical decision, we suggest that it probably reflects different task demands. In cued recall, participants receive a cue word and have to retrieve a (associated) target word presented during an earlier study phase. Producing a correct answer, thus, implies the activation of a specific word in its absence. Under such circumstances, the activation of associates might be harmful. According to Nelson and colleagues (Nelson et al. 1992; Nelson, McKinney, Gee, & Janczura, 1998), who have done the bulk of work on the influence of associates in cued recall, target words implicitly activate their associates during the study phase. Later in the test phase, the retrieval of a target word depends partially on its reactivation during an implicit search process. During this process the previously activated associates serve as competitors of the target word, resulting in an inhibitory influence of NoA (Nelson et al. 1992; Nelson et al., 1998). In contrast, in lexical decision the target word is present during task execution and the orthographic input will primarily drive the response and not the search for a previously presented word among memory traces. Furthermore, as mentioned above, lexical decisions might rely to some extent on the familiarity of a stimulus instead of unique identification (Balota & Chumbley, 1984), and the activation of associates might increase familiarity and thus lead to a facilitatory effect. In general, the facilitatory effect of NoA in lexical decision can be explained by models assuming that semantic activation – at least partially – determines lexical decisions (e.g., Masson, 1995; Plaut, 1997; Rodd, Gaskell, & Marslen-Wilson, 2004) or that feedback occurs from semantic to orthographic representations, whose activation then would determine lexical decisions

(Balota, Ferraro, & Connor, 1991). Although we interpret NoA as a measure reflecting semantic representation, it is important to note that other proposals situate associative relationships at the lexical-orthographic level and explain them by mere co-occurrence rather than semantic relatedness (Lupker, 1984; Moss, Hare, Day, & Tyler, 1994; Shelton & Martin, 1992). This position primarily relies on studies of priming that have found automatic priming for so-called pure associate pairs like *spider* - *web*, supposedly lacking a semantic relationship, whereas prime-target pairs with a semantic relationship but no measurable association showed no or reduced automatic priming. However, Hutchison (2003) noted that associated word pairs without any semantic relation are very rare. He also mentions that one can doubt that phrasal associates such as *spider* - *web*, often chosen as examples for pure associates, have no semantic relation at all, as the two words converge on a common concept. In line with Hutchison's observations, the associates included in the NoA count for our material show an additional semantic relationship. The associates for *giraffe* found in the Spanish database used by us (Fernández, Díez, & Alonso, 2006), for example, include among others its superordinate *animal*, the category coordinate *elephant*, the feature *tall*, and *zoo*, which might be interpreted as containing a script relationship (Moss, Ostrin, Tyler, & Marslen-Wilson, 1995; Schank & Abelson, 1977). Thus, it seems that the associates included in the NoA count would reflect semantic relations and that NoA therefore provides information about the semantic representation of a word. What is more, there is an extensive and continuing line of research using semantic associates to explore how meaning is accessed and how it is represented (some recent examples are: Holcomb & Grainger, 2009; Hutchison, Balota, Cortese, & Watson, 2008; Perea, Duñabeitia, & Carreiras, 2008; Rolke, Heil, Streb, & Henninghausen, 2001). In general, one can say that associates gained from the free association procedure are thought to reflect the semantic field of the cue word. Thus, NoA seems to be a suitable measure of overall semantic activation and therefore makes a good benchmark to which to compare the effect of orthographic neighborhood density on the ERP. As a supposedly semantic variable, we expect an N400 effect for NoA and if this is comparable to the orthographic neighborhood density N400 effect, this would support the notion that the orthographic neighborhood density effect reflects overall semantic activation. However, should the two effects differ then the orthographic neighborhood density N400 would seem to be of a different nature. A difference in the topography of the two effects would provide some evidence that different neural generators would be involved or the same neural generators to a different degree (McCarthy & Wood 1985; but see Urbach & Kutas, 2002). Orthographic neighborhood density and NoA might, for example, differentially engage brain areas linked to orthographic and semantic processing, which could lead to different scalp topographies of the ERP. There is some evidence that increases in N density lead to bigger competition at the orthographic level, whereas NoA does not. An increasing number of orthographic neighbors would not only result in more global lexical activation but also in a bigger set of orthographic candidates among which the word recognition system has to choose. The latter would be especially important in tasks requiring unique identification, such as perceptual identification or continuous word reading as measured by eye tracking. Indeed, studies employing these tasks have found an inhibitory effect for N density (Carreiras et al., 1997; Pollatsek et al. 1999; Snodgrass & Mintzer, 1993; but see Sears, Lupker, & Hino, 1999). By contrast, Duñabeitia et al. (2008) found facilitatory effects of NoA in perceptual identification and eye-movement measures, suggesting that NoA does not strongly affect competitive processes in word recognition (in contrast to the competitive processes seen in memory tasks).

Furthermore, it is known that the N400 window contains various negativities differentiated by their topography. The effect of concreteness on the ERP, for example, occurs as an enhanced negativity around 400 msec after target presentation with a frontal maximum.

However, the N400 effect related to other semantic manipulations is described as having a posterior and slightly right-lateralized maximum (Kounios & Holcomb, 1994; Kutas & Van Petten 1994; Swaab, Baynes, & Knight, 2002). Thus, the orthographic and associative neighborhood manipulations might differentially affect these negativities in the N400 window. One could also speculate that an eventual ERP effect of NoA would set in later than the effect of orthographic neighborhood density. In terms of an interactive activation model (McClelland & Rumelhart, 1981), the presentation of a word with many orthographic neighbors would first lead to an increased level of overall lexical activation because of the initial co-activation of orthographic neighbors based on the strong overlap in letter identity and letter position between such a word and its orthographic neighbors. The feedback to orthographic word units via shared letter units could then lead to a further increase in overall lexical activation. Assuming that the activation of associates takes place at the semantic level, the first moment that NoA would have an impact is, so to say, one level later than for orthographic neighborhood density.

Apart from the comparison with the ERP effect of orthographic neighborhood density, an ERP study on NoA is interesting in its own right and represents a valuable extension of the existing research on semantic processing in visual word recognition. The ERP, with its high temporal resolution, can give us information about the timing of the NoA effect. With the N400 we also have a well-studied component at hand that is related to semantic processing. Finding an effect of NoA on the N400 would reassure us that we are dealing with a semantic effect.

To summarize, this study has two purposes. First, to test the semantic-level interpretation of the orthographic neighborhood density N400 effect as proposed by Holcomb et al. (2002) by comparing the ERP elicited by a orthographic neighborhood density manipulation and a semantic manipulation as exemplified by associative neighborhood density. The respective hypothesis can be formulated like this: If the semantic-level explanation of the orthographic neighborhood density N400 effect is correct, manipulations of orthographic and associative density should result in similar N400 effects. The second purpose is to find an electrophysiological signature of NoA, which would potentially provide valuable information on the time course of this effect.

Method

Participants

Twenty-six native speakers of Spanish participated in the experiment (15 female), with an average age of 22.4 years (range 18-28 years). Participants were all students of the University of La Laguna and received course credit or payment for their participation. All were right handed according to a Spanish version of the Edinburgh Handedness Inventory and all had normal or corrected-to-normal vision.

Design

We used a 2 x 2 between-items design with all conditions realized within-participants. Factors were Type of Neighborhood (orthographic neighborhood density [N] /number of associates [NoA]) and Density (low/high).

Material

The material consisted of 200 Spanish words and 200 pseudowords. We used the free association norms published by Fernández et al. (2006) to compute NoA and the BuscaPalabras program to determine other lexical variables (Davis & Perea, 2005). Orthographic neighborhood density was manipulated within a subset of 100 words, with 50 ‘hermit’ words (e.g., Bowers et al., 2005; Grainger, 1990), such as *clavel* (nail), all having an N of zero and 50 words having a high N, such as *cera* (wax; mean N=9.5, range=3-23). The two word sets had a very similar NoA (means=14.1 and 14.6, respectively) and were further matched on frequency, length in letters, and imageability [2] (see Table 1). Associative neighborhood density was systematically varied for another subset of 100 words, with 50 words having a low NoA (mean=6.5, range=2-9), like *idioma* (language) and 50 words having a high NoA (mean=30.4, range=20-50), like *cuchara* (spoon). These 100 words were also matched on the above-mentioned variables, and had a similar orthographic neighborhood density (mean N=2.2 in both cases). Independent samples *t* tests comparing low and high density sets within each type of neighborhood for those variables showed the following results: comparison of N, orthographic set $t(98) = 10.78$, $p < .001$, associative set $t(98) = .06$, $p = .949$; comparison of NoA, orthographic set $t(98) = .93$, $p = .348$, associative set $t(98) = 20.81$, $p < .001$; comparison of number of higher frequency neighbors, orthographic set $t(98)=9.34$, $p < .001$, associative set $t(98) = 1.29$, $p =.199$; comparison of frequency, orthographic $t(98)= .01$, $p = .992$, associative set $t(98) = .03$, $p = .975$; comparison of number of letters, orthographic set $t(98) = 2.47$, $p = .015$ (within 1 SD), associative set $t(98) = .08$, $p = .933$; comparison of imageability, orthographic set $t(72)= .08$, $p = .938$, associative set $t(75)=3.88$, $p < .001$ (within 1 SD). Note that the differences in number of letters between low and high density items within the orthographic set were within 1 standard deviation, as well as the differences in imageability between low and high density items within the associative set. The difference in number of higher frequency neighbors within the orthographic set is a corollary of having chosen a very strong manipulation of orthographic neighborhood density, with all of the low-density items having no orthographic neighbor at all.

Pseudowords were created by changing 2 to 5 letters in the experimental words, resulting in *craver* and *odosia*, for example. The pseudowords had an average N of 1.5.

insert Table 1 about here

Procedure

Participants were seated in a dimly lit sound-attenuating room in front of a CRT monitor. Their task was to perform visual lexical decisions. A trial started with a plus sign as fixation presented for 500 ms, which was replaced by the target in capital letters. We chose to present stimuli in capital letters as this keeps the vertical visual angle constant across all letters and therefore across conditions. The target stayed on the screen for 500 ms and was followed by a 1000 ms blank screen. Next appeared a smiley face to indicate the rest period, which participants could use to blink. After 2000 ms the next trial began. Stimuli were presented in white uppercase New Courier letters against dark background. Viewing distance was approximately 90 cm and the maximum visual angle was about 2.1° horizontally and 0.4° vertically. Participants received the instruction to respond as fast as possible after the onset of the target without committing errors. They were further asked not to blink or move their eyes, except for the period when the smiley face was on the screen. They used a gamepad to give the word/pseudoword responses. There was a practice block comprising 20 trials (half words, half pseudowords) at the beginning of each session. All participants saw the entire set of 200 words and 200 pseudowords. To allow for breaks, the session was split up into 3 blocks of approximately equal size and an equal proportion of all conditions. The assignment of stimuli to blocks and trial order was randomized for each participant. One half of the participants were instructed to use the left index finger for word responses and the right index finger for pseudoword responses, whereas the remaining half received the opposite hand assignment.

EEG Recording and Analysis

The EEG was recorded from 58 sites on the scalp, referenced to the left mastoid. Scalp electrodes and a ground electrode on the forehead were mounted in an elastic cap manufactured by Electro-Cap International, Inc. For 33 electrodes the placement corresponded to the 10%-system of the American Electroencephalographic Society (1991) and for the rest to intermediate positions (see figure 1). Additional electrodes were placed at

insert figure 1 about here

the left and right mastoid. To monitor blinks and vertical eye movements 2 electrodes were placed above and below the left eye. Horizontal eye movements were monitored via 2 electrodes positioned external to the left and right outer canthus of each eye. Tin electrodes were used for all recordings. Electrode impedance was kept below 5 kΩ for the EEG recording and below 10 kΩ for the electrooculogram (EOG) recording. The signals were amplified by 2 BrainAmp amplifiers and data acquisition occurred via Vision Recorder software from Brain Products. The time constant was 10 s and the high-frequency cutoff was 120 Hz during recording. Digitization of the signals took place on-line with a sampling frequency of 250 Hz. The EEG was re-referenced offline to the average of the mastoid electrodes and filtered with a high frequency cutoff of 30 Hz and a slope of 24 dB/octave. Segments from 100 ms before to 1000 ms after stimulus onset were extracted from the continuous EEG. The 100 ms pre-stimulus period served as baseline and its average voltage per trial and electrode was subtracted from the respective waveforms. EOG and scalp electrodes were controlled for eye movement artifacts, muscular artifacts, drift, excessive alpha, and amplifier blocking. In a first step, an automatic procedure identified trials with values of 75 µV above or below baseline, with a voltage step of more than 50 µV from sample point to sample point (i.e. 4 ms), or with a voltage range of less than 0.5 µV during a 100 ms intervals. Additionally, a visual inspection of every trial took place. This led to the exclusion of on average 17.2 % of trials in the low-N condition, 15.7 % of trials in the high-N condition, 18.3 % of trials in the low-NoA condition, and 19.3 % of trials in the high-NoA condition, respectively. A one-way repeated measures ANOVA tested for differences in the exclusion rate across the four conditions and failed to show a significant effect. Trials with incorrect responses were also excluded from ERP analysis. Subject averages were then computed for all 4 experimental conditions. In order to test for topographic differences, estimates of the ERP in 9 scalp regions were obtained by averaging across corresponding electrodes. The 9 regions were a combination of the levels anterior, central, posterior with the levels left, midline, right and the electrodes included in the regions were: anterior-left (f3a, F3, F5, F7, c3a, c5a); anterior-right (f4a, F4, F6, F8, c4a, c6a); anterior-midline (Fz, cza); central-left (C3, C5, T3, c3p, tcp1, t3l); central-right (C4, C6, T4, c4p, tcp2, t4l); central-midline (Cz, pza); posterior-left (P3, P5, T5, p3p, cb1, O1); posterior-right (P4, P6, T6, p4p, cb2, O2); posterior-midline (Pz, Oz). Following Holcomb et al. (2002), analyses were done on average amplitude values in 2 different time windows corresponding to the N400 (350-550 ms) and the Late Positive Complex or LPC (550-850 ms). For each of these time windows there was a univariate repeated measures ANOVA analyzing activity in the midline regions, with the factors Type of Neighborhood, Density, and ACP (with the levels anterior, central, posterior). Additionally, an ANOVA on activity in the lateral regions was done for each time window, with the factors Type of Neighborhood, Density, ACP, and Hemisphere (with the levels left and right). Where appropriate violations of the assumption of sphericity were corrected using the Greenhouse-Geisser epsilon. We will only report significant effects that involve one of the experimental factors Type of Neighborhood or Density, leaving aside purely topographic effects. To follow up significant effects involving more than 2 means, we performed post-hoc *t* tests with a Sidak correction of the critical *p* value, keeping the familywise error rate at .05. We do not report the Sidak-corrected critical *p* values, if all testwise *p* values involved in a set of contrasts already lie above .05.

Results

Behavioral Results

We performed separate 2 x 2 univariate repeated measures ANOVAs on the RTs and error percentages of words, with the within-participants factors Type of Neighborhood (orthographic neighborhood [N] / number of associates [NoA]) and Density (low/high). Incorrect responses and RTs below 200 ms or above 1500 ms were excluded from the RT analysis (see table 2 for means of RT and errors). For the RT analysis the main effect of Density was significant, $F(1,25) = 14.42$, $MSE = 362.54$, $p = .001$. The average RT for high density words was 663 ms and 677 ms for low density words. Neither the main effect of Type of Neighborhood was significant ($F < 1$), nor the interaction of Type of Neighborhood by Density ($F(1,25) = 1.53$, $MSE = 321.63$, $p = .228$). The error analysis showed the same

insert table 2 about here

pattern, with only the main effect of Density reaching significance, $F(1,25) = 14.93$, $MSE = 188.46$, $p = .001$. On average, the error percentage was 5.2 for high density words and 7.9 for low density words. The ANOVA statistics for the main effect of Type of Neighborhood are $F(1,25) = 1.76$, $MSE = 7.02$, $p = .195$ and the interaction of Type of Neighborhood by Density had an $F < 1$.

A global comparison of words and pseudowords showed no significant difference in error percentage ($F < 1$), with an average of 6.5 % errors for words and 6.4% for pseudowords, respectively. However, the average RT of 670 ms for words differed significantly from the average of 749 ms for pseudowords, $F(1,25) = 58.05$, $MSE = 1410.16$, $p < .001$, showing the typical delay for pseudoword decisions.

ERP Results

Figure 2 contains grand average waveforms from 9 representative electrodes, showing the ERPs for high and low density items for the orthographic neighborhood density and the associative density manipulation. A broadly distributed negativity was clearly evident, peaking at around 400 ms after stimulus onset. This N400 showed a bigger amplitude for high-density words than for low-density words, most prominently at frontal sites. The N400 was followed by an LPC at central and posterior electrodes. This positivity showed a bigger amplitude for low-N words than for high-N words.

insert figure 2 about here

In the 350-550 ms window, the midline analysis showed a significant main effect of Density ($F(1,25) = 20.48$, $MSE = 5.36$, $p < .001$) and a significant interaction of Density with ACP ($F(2,50) = 13.63$, $MSE = .541$, $p < .001$, epsilon = .715). Overall, the N400 was more negative for high density words than low density words. To follow up the significant interaction, we tested the the simple effect of Density in all 3 midline regions. The testwise critical p value was set to .017, to ensure a familywise error rate of .05 across all three comparisons (Sidak correction). Density showed a significant effect in the anterior and central regions, but not in the posterior region (anterior: $t(25) = 5.86$, $p < .001$; central: $t(25) = 3.95$, $p = .001$; posterior: $t(25) = 2.44$, $p = .022$). For a topographical plot of the Density effect in this window, see figure 3, upper row. The critical comparisons regarding differential effects of orthographic and associative neighborhood density showed no significant outcomes. The main effect of Type of Neighborhood had an $F < 1$, the interaction of Type of Neighborhood by Density failed to reach significance with $F(1,25) = 2.97$, $MSE = 7.80$, $p = .097$, and the interaction of Type of Neighborhood with Density and ACP had again an $F < 1$. The lateral analysis of the 350-550 ms window also displayed a significant main effect of Density ($F(1,25) = 20.57$, $MSE = 5.29$, $p < .001$) and a significant interaction of Density by ACP ($F(2,50) = 12.13$, $MSE = .91$, $p = .001$, epsilon = .576). Pairwise comparisons within the ACP regions (critical p set to .017) showed significant differences for the anterior ($t(25) = 6.26$, $p < .001$), and central region ($t(25) = 4.0$, $p = .001$), but not for the posterior region ($t(25) = 1.8$, $p = .084$). There was also a significant interaction between Type of Neighborhood, ACP, and Hemisphere ($F(2,50) = 5.53$, $MSE = .068$, $p = .009$, epsilon = .891). Pairwise comparisons within the 6 regions involved showed no significant differences between orthographic neighborhood density and associative density items. Again, the critical comparisons concerning orthographic and associative neighborhood effects were not significant. The main effect of Type of Neighborhood had an $F < 1$ and the interaction Type of Neighborhood by Density failed to reach significance with $F(1,25) = 3.44$, $MSE = 8.35$, $p = .076$. Interactions of topographic factors with the term Type of Neighborhood x Density showed the following results: Hemisphere x Type of Neighborhood x Density, $F < 1$; ACP x Type of Neighborhood x Density, $F < 1$; Hemisphere x ACP x Type of Neighborhood x Density, $F(2,50) = 1.87$, $MSE = .05$, $p = .169$, epsilon = .905.

insert figure 3 about here

The analysis of the midline regions in the 550-850 ms window resulted in a significant main effect of Density ($F(1,25) = 16.18$, $MSE = 5.87$, $p < .001$) and a significant interaction of Type of Neighborhood, Density and ACP ($F(2,50) = 7.41$, $MSE = .42$, $p = .004$, epsilon =

.748). Exploring the origin of that interaction, pairwise comparisons in the ACP regions (6 comparisons, critical p set to .009) showed that the density effect in the orthographic neighborhood density condition was significant in all regions (all $ts(25) > -3.3$, $ps < .003$), whereas in the associative density condition it was not significant in any region (frontal: $t(25) = -2.2$, $p = .038$; central: $t(25) = -.65$, $p = .523$; posterior: $t(25) = -.2$, $p = .885$). To further explore the influence of ACP in this interaction, we compared the amplitude difference corresponding to the density effect pairwise between the 3 regions, for the orthographic neighborhood density items. However, there were no significant differences in effect size between regions (all $ts(25) < 1.23$, $ps < .235$). For a topographic plot of the density effect in this time window, see figure 3, lower row. In the lateral analysis, the main effect of Density came out significant ($F(1,25) = 18.24$, $MSE = 6.23$, $p < .001$), as well as the interactions between Type of Neighborhood, Density and ACP ($F(2,50) = 8.47$, $MSE = .68$, $p = .005$, epsilon = .596), Type of Neighborhood, ACP and Hemisphere ($F(2,50) = 7.44$, $MSE = .074$, $p = .002$, epsilon = .949), and Type of Neighborhood, Density, ACP and Hemisphere ($F(2,50) = 4.42$, $MSE = .086$, $p = .024$, epsilon = .837). We will only further explore this latter quadruple interaction, as technically the most complex interaction modifies all interactions that contain a subset of the factors involved. The analysis of the simple effects for Density in the 6 lateral regions (12 comparisons, critical p set to .004) showed that for orthographic neighborhood density differences were significant in the central and posterior regions (all $ts(25) > 3.54$, $ps < .003$), but not in the anterior regions (all $ts(25) < 2.82$, $ps > .009$). For associative density, the high/low Density differences were not significant in any region (all $ts(25) < 2.91$, $ps > .006$). As this does not explain the interaction with Hemisphere, we tested for left/right differences in the size of the Density effect, separately for associative and orthographic neighborhood density in the anterior, central, and posterior regions. However, none of the left/right differences turned out to be significant (all $ts(25) < 1.7$, $ps > .1$). Finally, we compared the high/low Density effect of associative neighborhood density and orthographic neighborhood density, separately for all 6 lateral regions. Together with all the previous contrasts, this amounted to 24 comparisons related to this quadruple interaction, so the critical *p* was set to .002. None of the pairwise comparisons reached significance (all *t*s(25) < 2.93, *p*s > .006).

Discussion

The current study examined the effects of orthographic neighborhood density and associative neighborhood density on behavioral measures and the ERP. Regarding the ERP, we also had the more specific aim of investigating whether orthographic and associative neighborhood density effects would be similar, which would support the idea that the ERP effect of orthographic neighborhood density (Holcomb et al., 2002) has a lexical-semantic origin. RT and percentage of errors in the lexical decision task showed an advantage of high density words over low density words. This was not modulated by Type of Neighborhood. In the ERP, we found an effect of Density in the N400 time window. High density words showed a bigger N400 than low density words in fronto-central regions, with a frontal maximum. Furthermore, the fact that there was no interaction with Type of Neighborhood indicates that orthographic and associative neighborhood density produced a similar effect [3]. This constitutes to our knowledge the first report of an ERP effect of associative neighborhood density. Furthermore, orthographic and associative neighborhood density displayed differential ERP activity in the 550-850 window. High-N items elicited a strong overall density effect with a posterior maximum, whereas there was no effect of density for the NoA manipulation in this window.

The facilitatory effect of orthographic and associative neighborhood density on lexical decisions replicates the results from numerous previous studies (cf. Andrews, 1997; Buchanan et al., 2001; Carreiras et al., 1997; Duñabeitia, Avilés et al., 2008; Locker et al., 2003; Yates et al., 2003; see also Duñabeitia, Marín, & Carreiras, in press, for a study testing orthographic and associative neighborhood density effects in healthy elderly persons and patients with mild Alzheimer's disease). Regarding the ERPs, we succeeded in replicating the orthographic neighborhood density effect in the N400 window found by Holcomb et al. (2002). Furthermore, associative neighborhood density led to a very similar effect in the 350-550 window. This suggests that the N400 effects of orthographic and associative neighborhood density originate from a common set of neural generators and are also functionally equivalent. Assuming that a manipulation of associative neighborhood density would primarily affect the lexical-semantic system (Buchanan et al.; Duñabeitia, Avilés et al.; Locker et al.; Yates et al.), one can conclude that the ERP effect of orthographic neighborhood density also reflects activity in the lexical-semantic system, as suggested by Holcomb et al. (2002). Our preferred interpretation for the present set of results is based on a semantic conception of the co-activation of the associative and orthographic neighbors of a given word. This assumption implies that NoA is specifically considered to have an effect at the semantic level. As stated in the introduction, it should be noted that some authors postulate that this is not necessarily the case (e.g., Lupker, 1984; Shelton & Martin, 1992) and that the relationship between two (or more) associates could be also understood in terms of contextual co-occurrence of the words involved. From this point of view, the relationship between associates might be implemented at the lexical-orthographic level and consequently the effect of NoA could occur at this level rather than at the semantic level. Under this assumption, the locus of the N400 effect of orthographic and associative neighborhood density could be the lexical-orthographic level or representation. However, there is a considerable amount of psycholinguistic literature using associates to investigate semantic representations, and previous work on NoA and on semantic associates in general has supported the conception that the associates of a word serve as (non-exclusive) constituents of that word’s semantic field (see Hutchinson, 2003).

Therefore, we believe that a semantic conception of the associative neighborhood is granted both by theoretical proposals and by previous evidence. Note that our position is far from operationalizing semantic similarity as mere frequency of co-occurrence. Rather, we conceive semantic similarity as a convolution of a numerous types of relationships among concepts, one of these being associative relationships.

Holcomb et al. (2002) interpreted the N400 effect of orthographic neighborhood density they found as reflecting overall semantic activation and related it to the MROM (Grainger & Jacobs, 1996). According to this model, facilitatory effects of N in the lexical decision task are based on the use of global lexical activation as an index of familiarity rather than on the unique identification of a particular word. A high global lexical activation would normally only occur for words as nonwords do not have lexical representations. Words with many orthographic neighbors lead to the activation of many orthographic word units, that is, a high global lexical activation, indicating a high word likeness of the presented letter string and supporting the fast guess that the letter string is a word. For words with few neighbors such a fast guess is not possible and they would show slower RTs accordingly. The word responses to low-N words would have to be based on the unique identification of that word, which in the MROM is modeled as the activation of the respective word node reaching a specific threshold value. An obvious question is whether the MROM explanation of N density effects on lexical decision could be extended to the NoA effects on this task. This seems feasible by adding a level with semantic units, where each node receives input from the corresponding node at the lexical orthographic level, and by further adapting the MROM in one of two ways. Either global activation at the orthographic level affects lexical decisions and there is an indirect influence of NoA through feedback from the semantic to the orthographic level (e.g., Balota et al., 1991), or global activation at the semantic level can directly influence lexical decisions. To decide between these two alternatives some detailed modeling work would be necessary to derive contrasting predictions and then test them empirically in a new study. Overall, the current findings seem consistent with the familiarity mechanism for lexical decisions proposed in the MROM. In the present study, increases in both orthographic and associative neighborhood led to stronger semantic activation as reflected by the N400, which could serve as an index of familiarity. Crucially, whereas the high-density condition produced stronger semantic activation than the low-density condition, it led to lower RTs than the low-density condition. This corresponds to the inverse pattern of familiarity and lexical decision times predicted by the MROM.

Others have offered an interpretation of semantic effects on lexical decision in terms of parallel distributed processing models (Borowsky & Masson, 1996; Locker et al., 2003; Mirman & Magnuson, 2008; Rodd et al. 2004). Within this framework, words are not represented as a particular node in a network, but rather as the pattern of activation across nodes in a network, where single nodes would represent orthographic, phonological or semantic features. In models with a semantic representation, activation spreads from an orthographic input layer to the nodes in a semantic layer and depending on the network architecture activation might also spread back to the orthographic layer (e.g., Seidenberg & McClelland, 1989). The possible activation patterns of a distributed network can be seen as a multidimensional space, wherein words form attractor basins (e.g., Masson, 1995). Once the network approaches the activation pattern corresponding to a particular word, it will be drawn closer and closer to that word pattern until it settles on the ground of the attractor basin. As a network is being drawn into a basin, measures of network energy decrease and such measures have actually been used to simulate response speed in lexical decision (Borowsky & Masson, 1996; Mirman & Magnuson, 2008; Plaut, 1997). Work by Rodd et al. suggests that words with broad attractor basins show faster lexical decisions because they start drawing the network into their basin early on. A dense associative neighborhood can be seen as being related to a broad attractor basin: Having many associates might indicate that there is overlap with many other concepts, which are close to each other. In this way, a distributed processing model with similar properties as the one implemented by Rodd et al. might also be able to explain the facilitative NoA effect in lexical decision. A decisive test for these proposals would be an actual simulation. Regarding orthographic neighborhood density, Sears, Hino, and Lupker (1999) were successful in simulating a facilitatory effect of orthographic neighborhood density with versions of the models by Seidenberg and McClelland (1989) and by Plaut, McClelland, Seidenberg, and Patterson (1996). Thus, distributed parallel processing models might also be able to simulate and explain the facilitatory effects of orthographic and associative neighborhood density on lexical decision times that have been found in our and other studies. The network energy measures used to simulate lexical decision times are often interpreted as measures of word familiarity, thus invoking a similar mechanism as the MROM, with familiarity driving lexical decisions rather than unique identification. How could network energy be related to the N400 effect? As outlined above dense neighborhoods might be related to reaching a low network energy level faster. At first sight it might appear contradictory that a low network-energy level should be reflected in an increased N400 (as we find for dense neighborhood words). However, it is doubtful that such a simple analogy between an abstract numerical index of a network state and N400 amplitude is granted. A low network energy level means a more ordered state of the network and this might very well be related to more synchronized and therefore stronger electrophysiological activity. All these considerations about the possible relation between connectionist networks and real neural networks are speculative hypotheses, though, and therefore need proper investigation before they can be considered valid explanations.

Regarding the N400 effect we found one might ask why it had a frontal maximum rather than showing the classical distribution with a posterior, slightly right-lateralized focus (cf. Kutas & Van Petten, 1994). Holcomb et al. (2002) do not report any significant interaction of the N400 effect with topographic factors. First, this means that they also failed to find a classical posterior distribution. Second, our study might have been somewhat more sensitive to topographical differences as we used a more extensive electrode montage. It is noteworthy that a frontal N400 effect has been consistently reported in experiments that compared concrete with abstract words (Kounios & Holcomb, 1994; Holcomb, Kounios, Anderson, & West, 1999; Swaab et al., 2002). Concrete words showed a bigger N400 than abstract words in these studies. As mentioned in the introduction, it has been suggested that concrete words have a richer semantic representation than abstract words, because of an additional imagistic code, a stronger link to context, or more semantic features (cf. Kieras, 1978; Paivio, 1991). In that sense, the well-known ERP concreteness effect and the density effect in our data might both be rooted in semantic richness and the corresponding stronger semantic activation. Note however, that the density effect in our data cannot be reduced to concreteness differences, as imageability was relatively well matched for high- and low-density words in general and particularly well for the items used in the manipulation of orthographic neighborhood density (see table 1). We would suggest that the frontal N400 or N400f may reflect the overall amount of lexical-semantic activation, whereas more posteriorly distributed N400 effects might rather indicate the integration of semantic information from multiple words, as in semantic priming or semantic congruency within a sentence. In line with this proposal, Swaab et al. (2002) and Holcomb et al. (1999) found a frontal N400 effect of concreteness, whereas at the same time semantic priming and semantic sentence congruency, respectively, resulted in a posterior N400 effect. Further research will have to determine whether a manipulation of semantic context crossed with a manipulation of N and NoA would lead to a similar dissociation of anterior and posterior N400 effects.

We have so far emphasized the similarities between orthographic and associative neighborhood density. However, there are also clear differences. The analysis of ERP activity in the 550-850 ms window showed a strong effect of orthographic neighborhood density with a clearly posterior maximum, whereas for NoA there was no effect of density. The posterior positivity showing the distinct effect of orthographic neighborhood density strongly resembles the P3b component (cf. Donchin & Coles, 1988; Squires, Squires, & Hillyard, 1975). This component typically occurs in response to task-relevant stimuli. Note that Holcomb et al. (2002) found a similar effect of orthographic neighborhood density, which, however, did not yield such a distinct topography in the statistical analysis as in our experiment. Some researchers have proposed that the P3b might reflect the consequences of a decision process (Squires, Hillyard, & Lindsay, 1973; Verleger, Jaskowski, & Wascher, 2005). Verleger et al., in particular, proposed that a fast decision how to classify a given stimulus would trigger a monitoring process that watches over the execution of the corresponding response. They suggest that the P3b reflects such a monitoring process, which would reach its peak near response execution. In terms of an interactive activation model as described above, the first stimulus classification could draw on early overall lexical activation as elicited by orthographic neighbors. Accordingly, a high-N word would be – preliminarily – classified as word and a low-N word as nonword. The preliminary classification of a stimulus as nonword might lead to distinct further processing such as an enhanced effort to reach unique identification, as words do exist that elicit little overall lexical activation. This could then result in an increased load on the hypothesized monitoring process and thus a bigger P3b for low-N words. Until further investigation, though, this explanation of the specific effect of orthographic neighborhood density on the LPC has only a post-hoc status.

Independent of the specific explanation of the LPC effect, however, one might draw some conclusions from the finding that it has a distribution which is clearly distinct from the

N400f effect and that it only occurs for the manipulation of orthographic neighborhood density and not of associative neighborhood density. First, Holcomb et al. found effects of orthographic neighborhood density on the N400 and the LPC which seemed to be equivalent in polarity and lack of topographic features. This made it possible to assume that the LPC effect was only a continuation of the N400 effect. By contrast, our results now suggest that the two effects reflect different processes. Secondly, the fact that only orthographic neighborhood density influenced the LPC indicates that it can trigger processes independently from the overall semantic activation as reflected in the N400 effect. Although this issue obviously needs more investigation, it provides information that can help constrain the construction of a complete picture of the processes of visual word recognition and their electrophysiological correlates.

In summary, we report an electrophysiological correlate of associative neighborhood density or NoA, manifesting itself as an increase of negative ERP amplitude for high-NoA words in the N400 time window, which has a frontal maximum. An equivalent effect occurred for a manipulation of orthographic neighborhood density. As the NoA effect very probably indicates overall semantic activation, it seems plausible that the N400 orthographic neighborhood density effect also takes place at the semantic level. This supports Holcomb et al.’s (2002) semantic interpretation of the N400 orthographic neighborhood density effect. In a later time window, the orthographic neighborhood density items elicited an LPC effect with posterior maximum that was absent for associative density items. The latter effect might be related to a monitoring process which is more intensive for low-N words, because the lack of an early surge in overall lexical activation makes them resemble nonwords.

References

Acha, J., & Perea, M. (2008). The effect of neighborhood frequency in reading: Evidence with transposed-letter neighbors. *Cognition, 108*(1), 290-300.

Adelman, J. S., Brown, G. D., & Quesada, J. F. (2006). Contextual diversity, not word frequency, determines word-naming and lexical decision times. *Psychological Science, 17*(9), 814-823.

American Encephalographic Society. (1991). Guidelines for standard electrode position nomenclature. *Journal of Clinical Neurophysiology, 8*(2), 200-202.

Andrews, S. (1997). The effect of orthographic similarity on lexical retrieval: Resolving neighborhood conflicts. *Psychonomic Bulletin & Review, 4*(4), 439-461.

Andrews, S. (1989). Frequency and neighborhood effects on lexical access: Activation or search? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 15*(5), 802-814.

Andrews, S. (1992). Frequency and neighborhood effects on lexical access: Lexical similarity or orthographic redundancy? *Journal of Experimental Psychology: Learning, Memory, and Cognition, 18*(2), 234-254.

Balota, D. A., & Chumbley, J. I. (1984). Are lexical decisions a good measure of lexical access? The role of word frequency in the neglected decision stage. *Journal of Experimental Psychology: Human Perception and Performance, 10*(3), 340-357.

Balota, D. A., Cortese, M. J., Sergent-Marshall, S. D., Spieler, D. H., & Yap, M. (2004). Visual word recognition of single-syllable words. *Journal of Experimental Psychology.General, 133*(2), 283-316.

Balota, D., Ferraro, F. R., & Connor, L. (1991). On the early influence of meaning in word recognition: A review of the literature. In P. Schwanenflugel (Ed.), *The psychology of word meaning* (pp. 187-222). Hillsdale, NJ: Lawrence Erlbaum Associates.

Boot, I., & Pecher, D. (2008). Word recognition is affected by the meaning of orthographic neighbours: Evidence from semantic decision tasks. *Language and Cognitive Processes, 23*(3), 375-393.

Borowsky, R., & Masson, M. E. J. (1996). Semantic ambiguity effects in word identification. *Journal of Experimental Psychology: Learning Memory and Cognition, 22*(1), 63-85.

Bowers, J. S., Davis, C. J., & Hanley, D. A. (2005). Interfering neighbours: The impact of novel word learning on the identification of visually similar words. *Cognition, 97*(3), B45-54.

Brown, C., & Hagoort, P. (1993). The processing nature of the N400: Evidence from masked priming. *Journal of Cognitive Neuroscience, 5* (1), 34-44.

Buchanan, L., Westbury, C., & Burgess, C. (2001). Characterizing semantic space: Neighborhood effects in word recognition. *Psychonomic Bulletin & Review, 8*(3), 531-544.

Carreiras, M., Perea, M., & Grainger, J. (1997). Effects of orthographic neighborhood in visual word recognition: Cross-task comparisons. *Journal of Experimental Psychology: Learning , Memory, and Cognition, 23*(4), 857-871.

Coltheart, M., Davelaar, E., Jonasson, J., & Besner, D. (1977). Access to the internal lexicon. In S. Dornic (Ed.), *Attention and performance VI* (pp. 535-555). Hillsdale, NJ: Lawrence Erlbaum Associates.

Davis, C. J., & Perea, M. (2005). BuscaPalabras: A program for deriving orthographic and phonological neighborhood statistics and other psycholinguistic indices in spanish. *Behavior Research Methods, 37*(4), 665-671.

Davis, C. J., & Taft, M. (2005). More words in the neighborhood: Interference in lexical decision due to deletion neighbors. *Psychonomic Bulletin & Review, 12*(5), 904-910.

Donchin, E., & Coles, M. G. H. (1988). Is the P300 component a manifestation of context updating? *Behavioral and Brain Sciences, 11*(3), 357-374.

Duñabeitia, J. A., Avilés, A., & Carreiras, M. (2008). NoA's ark: Influence of the number of associates in visual word recognition. *Psychonomic Bulletin & Review, 15*, 1072-1077.

Duñabeitia, J. A., Carreiras, M., & Perea, M. (2008). Are coffee and toffee served in a cup? Ortho-phonologically mediated associative priming. *Quarterly Journal of Experimental Psychology, 61* (12), 1861-1872.

Duñabeitia, J. A., Marín, A., & Carreiras, M. (in press). Associative and orthographic neighborhood density effects in normal aging and Alzheimer's disease. *Neuropsychology*.

Duñabeitia, J. A., & Vidal-Abarca, E. (2008). Children like dense neighborhoods: Orthographic neighborhood density effects in novel readers. *The Spanish Journal of Psychology, 11*(1), 26-35.

Fernández, A., Díez, E. & Alonso, M. Á. (2006). *Normas de asociación libre en castellano de la Universidad de Salamanca.* Retrieved September 14, 2007, from http://www.usal.es/~gimc/normas/nipejcyl.htm

Grainger, J. (1990). Word-frequency and neighborhood frequency-effects in lexical decision and naming. *Journal of Memory and Language, 29*(2), 228-244.

Grainger, J., & Jacobs, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review, 103*(3), 518-565.

Holcomb, P. J. (1993). Semantic priming and stimulus degradation: Implications for the role of the N400 in language processing. *Psychophysiology, 30*, 47-61.

Holcomb, P. J., & Grainger, J. (2009). ERP effects of short interval masked asscociative and repetition priming. *Journal of Neurolinguistics, 22*, 301-312.

Holcomb, P. J., Grainger, J., & O'Rourke, T. (2002). An electrophysiological study of the effects of orthographic neighborhood size on printed word perception. *Journal of Cognitive Neuroscience, 14*(6), 938-950.

Holcomb, P. J., Kounios, J., Anderson, J. E., & West, W. C. (1999). Dual-coding, context-availability, and concreteness effects in sentence comprehension: An electrophysiological investigation. *Journal of Experimental Psychology: Learning, Memory, and Cognition, 25*(3), 721-742.

Hutchison, K. A. (2003). Is semantic priming due to association strength or feature overlap? A microanalytic review. *Psychonomic Bulletin & Review, 10*(4), 785-813.

Hutchison, K. A., Balota, D. A., Cortese, M. J., & Watson, J. M. (2008). Predicting semantic priming at the item level. *Quarterly Journal of Experimental Psychology, 61* (7), 1036-1066.

Kieras, D. (1978). Beyond pictures and words - alternative information-processing models for imagery effects in verbal memory. *Psychological Bulletin, 85*(3), 532-554.

Kounios, J., & Holcomb, P. J. (1994). Concreteness effects in semantic processing: ERP evidence supporting dual-coding theory. *Journal of Experimental Psychology: Learning , Memory, and Cognition, 20*(4), 804-823.

Kutas, M., & Federmeier, K.D. (2000). Electrophysiology reveals semantic memory use in language comprehension. *Trends in Cognitive Sciences, 4* (12), 463-470.

Kutas, M., & Van Petten, C. (1994). Psycholinguistics electrified: Event-related brain potential investigations. In M.A. Gernsbacher (Ed.), *Handbook of psycholinguistics* (pp. 83-143). San Diego, CA: Academic Press.

Lavidor, M., Johnston, R., & Snowling, M. J. (2006). When phonology fails: Orthographic neighbourhood effects in dyslexia. *Brain and Language, 96*(3), 318-329.

Laxon, V., Coltheart, V., & Keating, C. (1988). Children find friendly words friendly too: Words with many orthographic neighbours are easier to read and spell. *British Journal of Educational Psychology, 58*, 103-119.

Locker, L.,Jr, Simpson, G. B., & Yates, M. (2003). Semantic neighborhood effects on the recognition of ambiguous words. *Memory & Cognition, 31*(4), 505-515.

Lund, K., & Burgess, C. (1996). Producing high-dimensional semantic spaces from lexical co-occurrence. *Behavior Research Methods, Instruments, & Computers, 28*(2), 203-208.

Lupker, S. J. (1984). Semantic priming without association: A second look. *Journal of Verbal Learning and Verbal Behavior, 23*(6), 709-733.

Masson, M. E. J. (1995). A distributed-memory model of semantic priming. *Journal of Experimental Psychology: Learning Memory and Cognition, 21*(1), 3-23.

McCarthy, G., & Wood, C. C. (1985). Scalp distributions of event-related potentials: An ambiguity associated with analysis of variance models. *Electroencephalography and Clinical Neurophysiology, 62*(3), 203-208.

McClelland, J. L., & Rumelhart, D. E. (1981). An interactive activation model of context effects in letter perception .1. an account of basic findings. *Psychological Review, 88*(5), 375-407.

McDonald, S. A., & Shillcock, R. C. (2001). Rethinking the word frequency effect: The neglected role of distributional information in lexical processing. *Language and Speech, 44*(Pt 3), 295-323.

Mirman, D., & Magnuson, J. S. (2008). Attractor dynamics and semantic neighborhood density: Processing is slowed by near neighbors and speeded by distant neighbors.

Journal of Experimental Psychology: Learning , Memory, and Cognition, 34(1), 65-79.

Moss, H. E., Hare, M., Day, P., & Tyler, L. (1994). A distributed memory model of the associative boost in semantic priming. *Connection Science, 6*(4), 413-427.

Moss, H. E., Ostrin, R. K., Tyler, L. K., & Marslenwilson, W. D. (1995). Accessing different types of lexical semantic information - evidence from priming. *Journal of Experimental Psychology: Learning Memory and Cognition, 21*(4), 863-883.

Nelson, D. L., McKinney, V. M., Gee, N. R., & Janczura, G. A. (1998). Interpreting the influence of implicitly activated memories on recall and recognition. *Psychological Review, 105* (2), 299-324.

Nelson, D. L., Schreiber, T. A., & McEvoy, C. L. (1992). Processing implicit and explicit representations. *Psychological Review, 99*(2), 322-348.

Paivio, A. (1991). Dual coding theory - retrospect and current status. *Canadian Journal of Psychology-Revue Canadienne De Psychologie, 45*(3), 255-287.

Pecher, D., Zeelenberg, R., & Wagenmakers, E. J. (2005). Enemies and friends in the neighborhood: Orthographic similarity effects in semantic categorization. *Journal of Experimental Psychology: Learning , Memory, and Cognition, 31*(1), 121-128.

Perea, M., Duñabeitia, J. A., & Carreiras, M. (2008). Masked associative/semantic priming effects across languages with highly proficient bilinguals. *Journal of Memory and Language, 58*, 916-930.

Pexman, P. M., Hargreaves, I., Siakaluk, P., Bodner, G., & Pope, J. (2008). There are many ways to be rich: Effects of three measures of semantic richness on visual word recognition. *Psychonomic Bulletin & Review, 15*(1), 161-167.

Pexman, P. M., Holyk, G. G., & Monfils, M. H. (2003). Number-of-features effects and semantic processing. *Memory & Cognition, 31*(6), 842-855.

Pexman, P. M., Lupker, S. J., & Hino, Y. (2002). The impact of feedback semantics in visual word recognition: Number-of-features effects in lexical decision and naming tasks. *Psychonomic Bulletin & Review, 9*(3), 542-549.

Plaut, D. C. (1997). Structure and function in the lexical system: Insights from distributed models of word reading and lexical decision. *Language and Cognitive Processes, 12*(5-6), 765-805.

Plaut, D. C., McClelland, J. L., Seidenberg, M. S., & Patterson, K. (1996). Understanding normal and impaired word reading: Computational principles in quasi-regular domains. *Psychological Review, 103*(1), 56-115.

Pollatsek, A., Perea, M., & Binder, K. S. (1999). The effects of "neighborhood size" in reading and lexical decision. *Journal of Experimental Psychology: Human Perception and Performance, 25*(4), 1142-1158.

Rodd, J. M. (2004). When do leotards get their spots? semantic activation of lexical neighbors in visual word recognition. *Psychonomic Bulletin & Review, 11*(3), 434-439.

Rodd, J. M., Gaskell, M. G., & Marslen-Wilson, W. D. (2004). Modelling the effects of semantic ambiguity in word recognition. *Cognitive Science, 28*(1), 89-104.

Rolke, B., Heil, M., Streb, J., & Hennighausen, E. (2001). Missed prime words within the attentional blink evoke an N400 semantic priming effect. *Psychophysiology, 38*, 165-174.

Schank, R., & Abelson, R. P. (1977). *Scripts, plans, goals and understanding*. Hillsdale, NJ: Erlbaum.

Sears, C. R., Lupker, S. J., & Hino, Y. (1999). Orthographic neighborhood effects in perceptual identification and semantic categorization tasks: A test of the multiple read-out model. *Perception & Psychophysics, 61*(8), 1537-1554.

Sears, C., Hino, Y., & Lupker, S. J. (1999). Orthographic neighbourhood effects in parallel distributed processing models. *Canadian Journal of Experimental Psychology, 53*(3), 220-230.

Seidenberg, M. S., & McClelland, J. L. (1989). A distributed, developmental model of word recognition and naming. *Psychological Review, 96*(4), 523-568.

Shelton, J. R., & Martin, R. C. (1992). How semantic is automatic semantic priming? *Journal of Experimental Psychology: Learning , Memory, and Cognition, 18*(6), 1191-1210.

Siakaluk, P. D., Sears, C. R., & Lupker, S. J. (2002). Orthographic neighborhood effects in lexical decision: The effects of nonword orthographic neighborhood size. *Journal of Experimental Psychology: Human Perception and Performance, 28*(3), 661-681.

Snodgrass, J. G., & Mintzer, M. (1993). Neighborhood effects in visual word recognition: Facilitatory or inhibitory? *Memory & Cognition, 21*(2), 247-266.

Squires, K. C., Hillyard, S. A., & Lindsay, P. H. (1973). Vertex potentials evoked during auditory signal-detection - relation to decision criteria. *Perception & Psychophysics, 14*(2), 265-272.

Squires, N. K., Squires, K. C., & Hillyard, S. A. (1975). Two varieties of long-latency positive waves evoked by unpredictable auditory-stimuli in man. *Electroencephalography and Clinical Neurophysiology, 38*(4), 387-401.

Swaab, T. Y., Baynes, K., & Knight, R. T. (2002). Separable effects of priming and imageability on word processing: An ERP study. *Cognitive Brain Research, 15*(1), 99-103.

Urbach, T. P., & Kutas, M. (2002). The intractability of scaling scalp distributions to infer neuroelectric sources. *Psychophysiology, 39*(6), 791-808.

Verleger, R., Jaskowski, P., & Wascher, E. (2005). Evidence for an integrative role of P3b in linking reaction to perception. *Journal of Psychophysiology, 19*(3), 165-181.

Yates, M., Locker, L.,Jr, & Simpson, G. B. (2003). Semantic and phonological influences on the processing of words and pseudohomophones. *Memory & Cognition, 31*(6), 856-866.

Author note

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Footnotes

1. The definition of the orthographic neighborhood has been extended as a consequence of recent findings, and other types of neighbors have been also included into the orthographic neighborhood, like addition, deletion or transposition neighbors (e.g., Acha & Perea, 2008; Bowers et al. 2005; Davis & Taft, 2005). For simplicity, we will solely refer to substitution neighbors here.
2. The BuscaPalabras database did only contain imageability values for 151 of the 200 words used in the experiment. Therefore, we administered an imageability questionnaire including all 200 words to a group of 20 volunteers. The results showed that, as with the scores from BuscaPalabras, the mean imageability value was very similar across conditions.
3. In the midline and lateral analysis of the 350-550 ms window, the respective interactions of Density by Type of Neighborhood were nearly significant. To assure that both orthographic and asscociative neighborhood density actually produced a Density effect, we performed an analysis of simple effects of Density for both types of neighborhood. We did this for the anterior midline region and the anterior lateral region, as the significant Density by ACP interactions for midline and lateral had indicated that the Density effect was strongest there. For the anterior midline region, both the simple effect of Density for orthographic neighborhood density ($t(25) = 5.17$, $p < .001$) and for associative neighborhood density ($t(25) = 2.35$, $p = .027$) reached significance. The simple effects in the lateral anterior region were also significant for orthographic neigborhood density ($t(25) = 4.7$, $p < .001$) and associative neighborhood density ($t(25) = 2.61$, $p = .015$). There might be differences in the amplitude of the N400 effects, of course, as figure 3 suggests. However, for our conlusions it is sufficient that orthographic and asscociative neighborhood density both produce N400 effects and that

these effects have a similar distribution – they do not necessarily have to be of the same size. The latter actually would seem hard to achieve, as it is presently unknown which difference in number of associates would produce an N400 effect (or RT effect) of the same size as a given difference in number of orthographic neighbors.

Table 1. Average values for lexical statistics of the experimental words in the 4 conditions, with standard deviations in parentheses.

Type of Neighborhood	Density	N[a]	NoA[b]	HFN[c]	Frequency	Letters	IMG[d]
Orthographic	Low	0 (0)	14.1 (2.6)	0 (0)	14.5 (16.1)	5.8 (0.7)	5.3 (0.8)
	High	9.5 (6.3)	14.6 (3.1)	1.6 (1.2)	14.5 (12.2)	5.3 (1.3)	5.3 (1.0)
Associative	Low	2.2 (3.1)	6.5 (1.9)	0.5 (1.3)	13.7 (11.8)	6.1 (1.2)	5.2 (0.8)
	High	2.2 (3.2)	30.4 (8.0)	1.0 (2.0)	13.7 (17.2)	6.1 (1.2)	5.9 (0.7)

[a] number of orthographic neighbors

[b] number of associates

[c] number of higher frequency orthographic neighbors

[d] Imageability

Table 2. Means of RT and error percentage for the 4 experimental conditions, with standard deviations in parentheses.

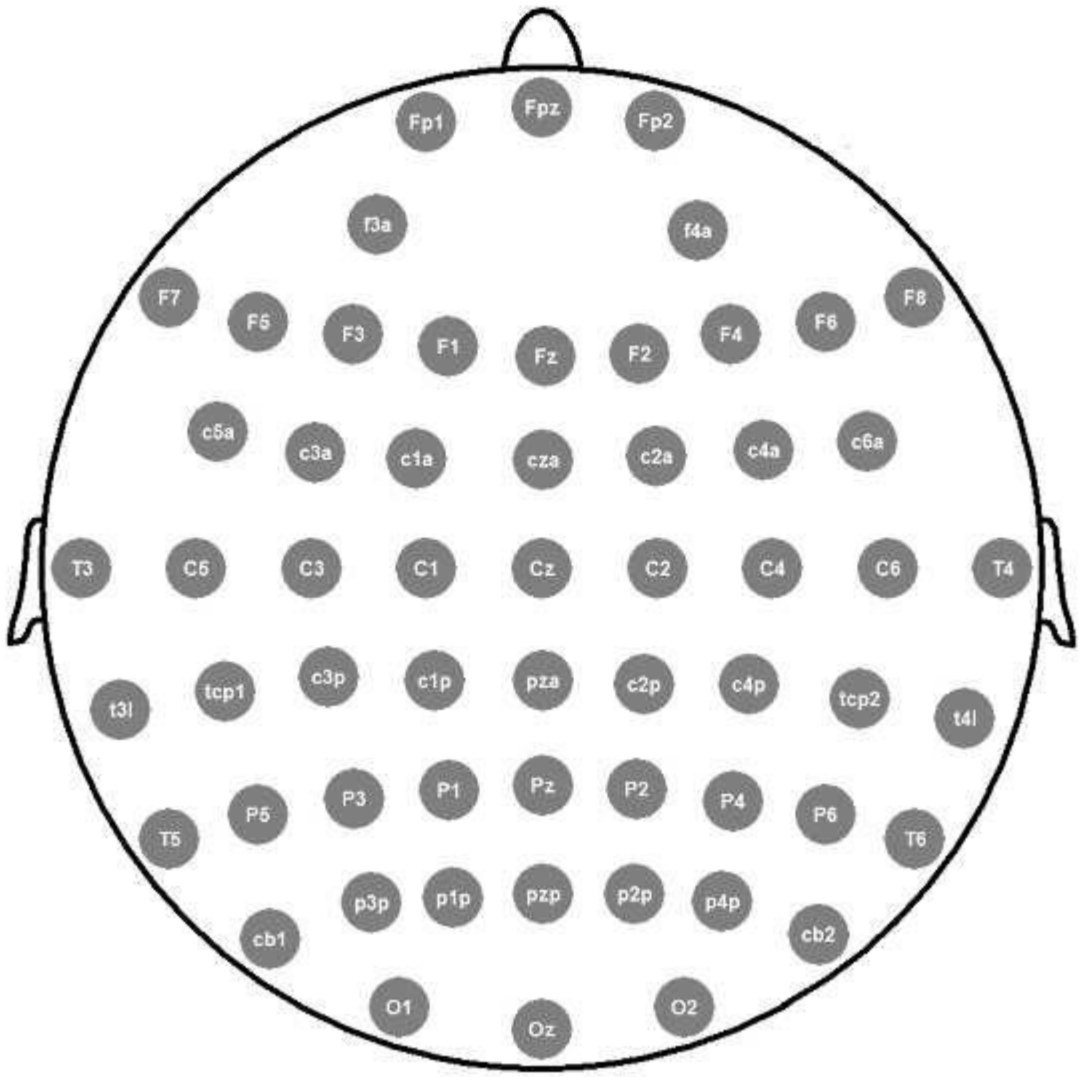
Type of Neighborhood	Density	RT [ms]	Error [%]
Orthographic	Low	674 (83)	8.1 (6.8)
	High	664 (89)	5.7 (5.1)
Associative	Low	680 (90)	7.7 (7.4)
	High	661 (97)	4.7 (6.0)

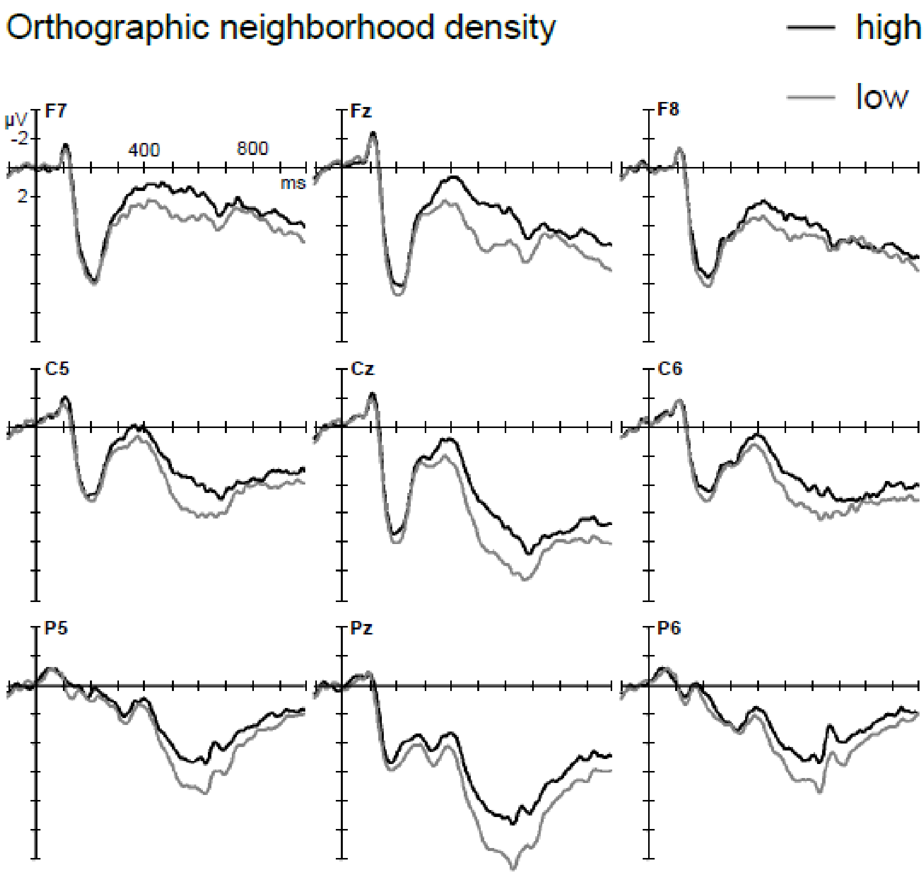
Figure Captions

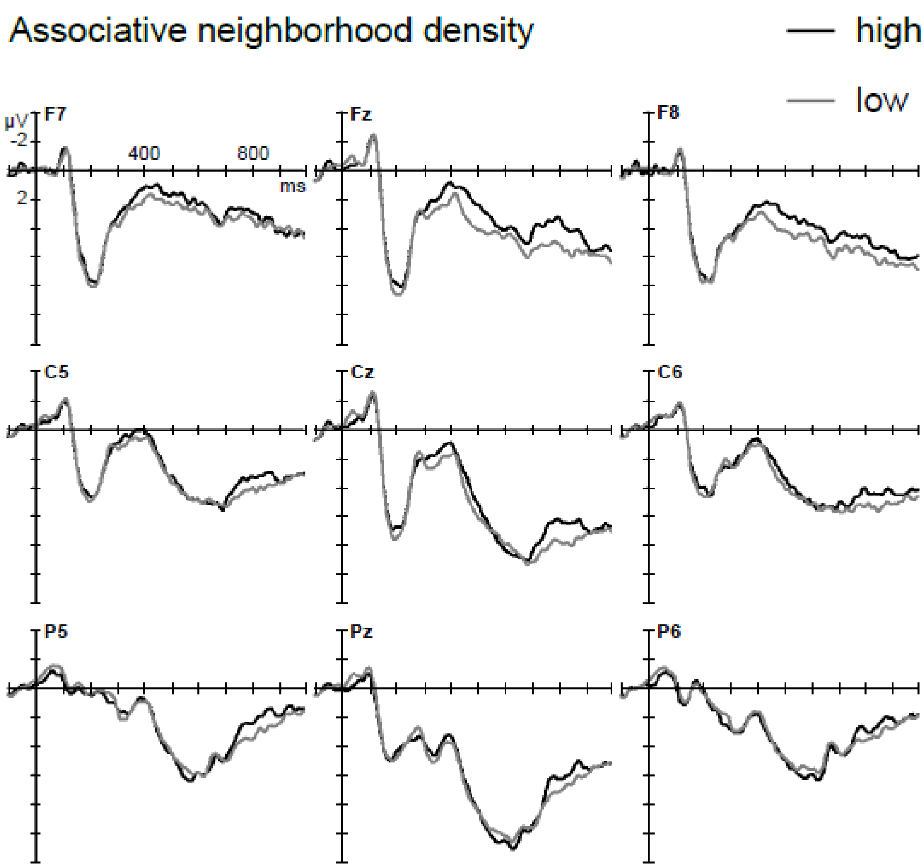
Figure 1. Schema of electrode positions in the electro-cap as used for EEG measurement.

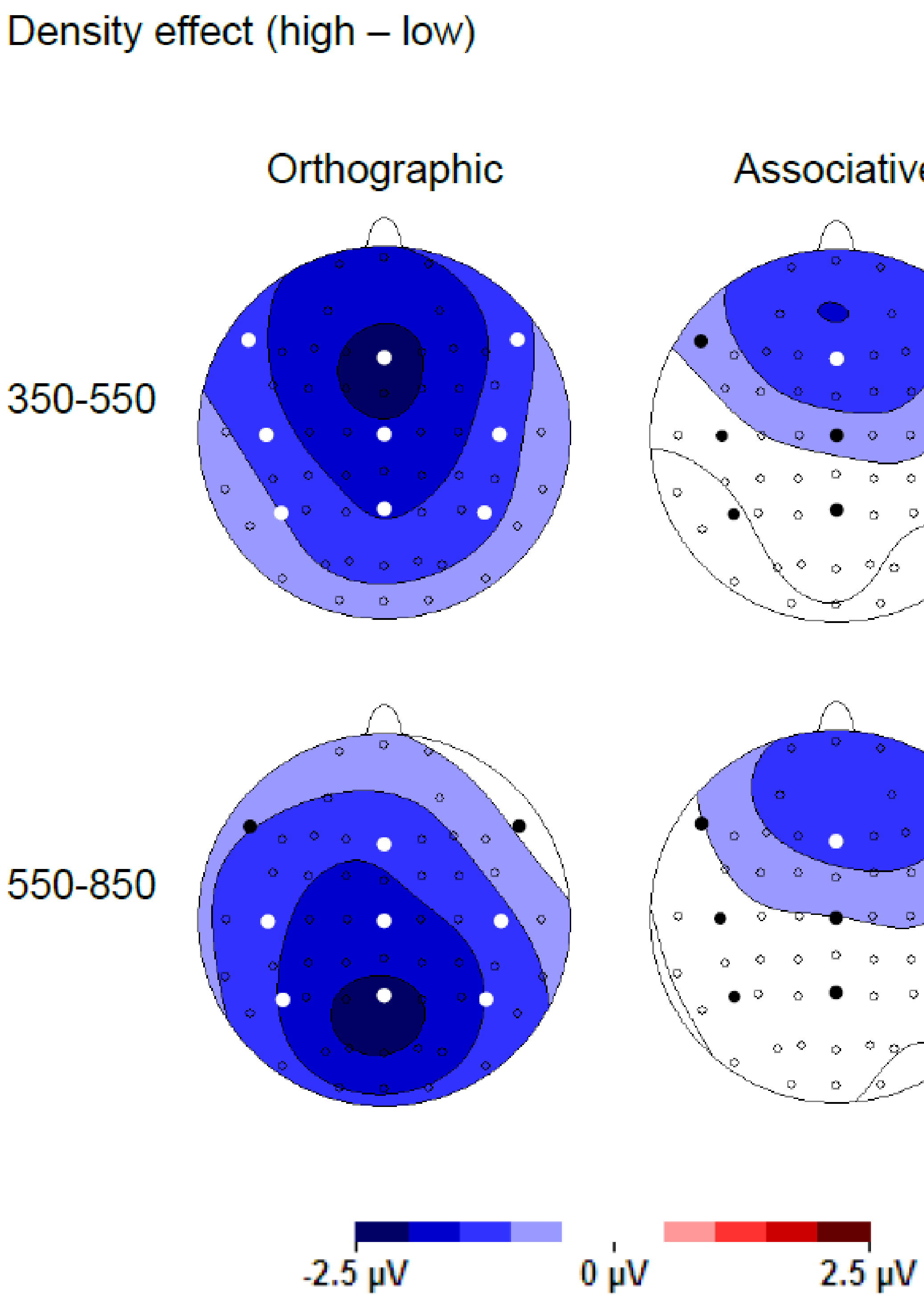
Figure 2. ERP waveforms of 9 representative electrodes, showing the high/low density contrast for orthographic neighborhood density (upper panel) and associative neighborhood density (lower panel). Negative voltage is up.

Figure 3. Topographic plots of the density effect (high density – low density), for orthographic neighborhood density and associative neighborhood density, respectively. Activity is averaged across the time windows of 350-550 ms (upper row) and 550-850 ms (lower row). Filled circles indicate the positions of the electrodes displayed in figure 1 and unfilled circles indicate the positions of the remaining electrodes used. Interpolation is spline-based. Step size between isovoltage lines is 0.5 µV.


Fpz
Fp1
Fp2
f3a
f4a
F7
F5
F3
F1
Fz
F2
F4
F6
F8
c5a
c3a
c1a
cza
c2a
c4a
c6a
T3
C5
C3
C1
Cz
C2
C4
C6
T4
t3l
tcp1
c3p
c1p
pza
c2p
c4p
tcp2
t4l
T5
P5
P3
P1
Pz
P2
P4
P6
T6
cb1
p3p
p1p
pzp
p2p
p4p
cb2
O1
Oz
O2


Orthographic neighborhood density
high
low
µV
-2
2
400
800
ms
F7
Fz
F8
C5
Cz
C6
P5
Pz
P6


Associative neighborhood density
high
low
µV
-2
2
400
800
ms
F7
Fz
F8
C5
Cz
C6
P5
Pz
P6


Density effect (high – low)
Orthographic
Associative
350-550
550-850
-2.5 µV
0 µV
2.5 µV