Brain and Language 108 (2009) 191–196

Contents lists available at ScienceDirect

Brain and Language

journal homepage: www.elsevier.com/locate/b&l

Short Communication

Lexical access in early stages of visual word processing: A single-trial correlational MEG study of heteronym recognition

Olla Solomyak *, Alec Marantz

New York University, Department of Linguistics, 726 Broadway, 7th Floor, New York, NY 10003, USA

ARTICLE INFO

Article history:
Accepted 9 September 2008
Available online 11 November 2008

Keywords:
MEG
Visual word recognition
Lexical access
M170
Heteronym

ABSTRACT

We present an MEG study of heteronym recognition, aiming to distinguish between two theories of lexical access: the 'early access' theory, which entails that lexical access occurs at early (pre 200 ms) stages of processing, and the 'late access' theory, which interprets this early activity as orthographic word-form identification rather than genuine lexical access. A correlational analysis method was employed to examine effects of the heteronyms' form and lexical properties on brain activity. We find support for the 'late access' view, in that lexical properties did not affect processing until after 300 ms, while earlier activation was primarily modulated by orthographic form.

1. Introduction

Accounts of visual word recognition differ as to the nature of the neural processing involved within 200 ms of visual word presentation and as to the nature of the representations accessed during this early processing. On the one hand, some theories suppose that early processing makes contact with lexical entries for words that include semantic and phonological properties, such that lexical frequency, semantic features and lexicality itself affect neural computation around 100 ms post-stimulus onset in a visual word recognition task (Hauk, Davis, Ford, Pulvermüller, & Marslen-Wilson, 2006; Penolazzi, Hauk, & Pulvermüller, 2007; Pulvermüller, Assadollahi, & Elbert, 2001; Sereno, Rayner, & Posner, 1998). On the other hand, theories such as that associated with Cohen, Dehaene and colleagues suggest that early processing of visually presented words involves bottom-up visual feature detection leading to visual word-form recognition, but not necessarily access to the semantic lexicon, within the first stages of lexical access (Dehaene, Cohen, Sigman, & Vinckier, 2005; Pylkkänen & Marantz, 2003; Vinckier et al., 2007). The word-form representations themselves might consist of sets of bigram, trigram or higher order combinations of (abstract) letter representations.

Heteronyms like "wind" (either 'a strong breeze' or 'to move along a twisted path,' depending on the pronunciation)—homographs that are not also homophones—present a possible testing ground for distinguishing the two hypotheses about early word recognition, the one proposing access to the semantic lexicon within 150 ms or so of stimulus onset, the other proposing bottom-up recognition through access to a visual word-form around 170 ms post-stimulus. For the early access theories, the ambiguity of heteronyms should be relevant at the early stages of visual word recognition. In particular, the relative frequency of the different meanings of such heteronyms might be expected to affect processing by 170 ms. On the other hand, for theories that suppose early processing of visually presented words should involve first access to a visual word-form stored in terms of abstract letter patterns, followed by activation of the semantic lexicon, the special properties of the heteronyms might be relevant only after the early stages of processing, with the heteronyms behaving early like non-heteronyms with the same visual form frequency.

We report the results of an MEG lexical decision experiment with heteronyms designed to test these competing theories. In particular, we ask which brain activation from regions and time frames associated with visual word recognition correlates with the special properties of these words. Brain activity associated with access to a lexicon distinguishing words spelled the same but pronounced differently should show correlations with the relative frequency of the meanings of (words represented by) the heteronyms. Brain activity associated with processing of visual word-forms independent of the semantic (and phonological) lexicon should only correlate with frequency properties of the word-forms of the heteronyms.

Particularly through the work of Tarkiainen et al., a coherent picture of neural processing in early stages of visual word recognition is emerging from the ERP/MEG literature. Within 100 ms of stimulus onset, visual processing areas in the occipital lobe are active, with activity correlating with the low level visual complexity of the input (the so-called Type I response of Tarkiainen et al.) (Cornelissen, Tarkiainen, Helenius, & Salmelin, 2003; Tarkiainen, Cor-

* Corresponding author.
E-mail address: os17@nyu.edu (O. Solomyak).

0093-934X/$ - see front matter © 2008 Elsevier Inc. All rights reserved.
doi:10.1016/j.bandl.2008.09.004

nelissen, & Salmelin, 2002; Tarkiainen, Helenius, Hansen, Cornelissen, & Salmelin, 1999). Within 130 ms or so, activity has spread to the occipital/temporal regions of the brain, with activity correlated at least to the distinction between letter strings and symbol strings (the Type II response of Tarkiainen et al., 1999, also sometimes referred to as the letter string response). By 170 ms, activity has spread along the ventral surface of the temporal lobes, including the "visual word-form area" that Cohen et al.'s fMRI studies have identified (Cohen & Dehaene, 2004; Dehaene, Le Clec, Poline, Le Bihan, & Cohen, 2002). By this latency, inferior temporal areas have also begun to show stimulus-related activity (see e.g., Pammer et al., 2004). Examination of peaks in the MEG signal from MEG sensors has led also to the identification of response components to visual words at around 250 and 350 ms post-stimulus onset (Pylkkänen & Marantz, 2003). In dipole localization analyses of MEG data, these components localize to temporal regions, including classically defined Wernicke's area.

For this study, we focus on the "M170" response component as well as later activity associated with the M350 component from the literature and with brain regions associated with word recognition. For each neural response identified from the grand average of MEG responses across subjects and words, following the lead of Hauk et al. (2006), we correlate the brain activity at that component with continuous stimulus variables tied to the competing hypothesis about lexical access in visual word recognition. In particular, the early lexical access hypothesis should predict an effect of the relative frequency of the meanings of the heteronyms on the M170 while the late access theory predicts that only variables associated with the visual form of the words should correlate with the M170. On the late access theory, the special properties of the heteronyms should become relevant after the M170, in areas associated with orthography to phonology conversion and in more superior temporal areas associated with the "rich" lexicon, as well as, perhaps, the inferior frontal areas reported in previous research on reading (Marinkovic, 2004; Pammer et al., 2004).

The correlational analysis method that we employ in the current study is a novel approach to MEG data analysis, although it is based in part on the approach of Hauk et al. (2006) to ERP sensor-space data analysis and relies on a standard minimum norm distributed source model for MEG source reconstruction (MNE, MGH/HMS/MIT Athinoula A. Martinos Center for Biomedical Imaging, Charleston, MA). Rather than comparing groups of words that are split based on dimensions of interest, we focus on the effects of properties that vary continuously *within* a group of words by correlating the variables of interest directly with brain activity in brain regions and time frames of interest. This correlational analysis technique is especially advantageous in the study of linguistic properties, which are often not balanced across groups of words. In particular, trying to control simultaneously for several potentially significant variables often results in small numbers of candidate stimuli for some cells in a factorial design, for which the notion of random sampling is therefore meaningless (Baayen, 2004). The study of heteronyms presents this problem—the stimuli used in the current experiment are chosen from an extremely limited set of words, and therefore do not represent an unbiased sample. The correlational analysis method introduced here allows us to exploit the unique properties of heteronyms to address an important question about early visual word recognition without violating the assumptions of inferential statistics.

2. Methods

Nine subjects participated in the current study, which consisted of a lexical decision task with concurrent MEG recording. Twenty mono-morphemic heteronyms comprised the target stimuli for the study.[1] Each heteronym had two distinct pronunciations with unrelated meanings. These were presented along with 20 mono-morphemic controls, and 40 non-words. Control words were matched to the heteronyms on frequency, length and bigram frequency.[2] Non-words were matched to the entire group of words on length and bigram frequency. Orthographic properties of the word-forms were computed from the CELEX Lexical Database (Baayen, Piepenbrock, & Gulikers, 1995), including open-bigram frequency (the average frequency of both adjacent and non-adjacent pairs of letters appearing in a particular order within a word) and trigram frequency (see Dehaene et al., 2005). Lexical frequencies for the individual meanings of each heteronym were also obtained from CELEX, which contains separate entries for phonologically distinct words.

The "heteronym frequency ratio", defined as the ratio of the higher of each heteronym's lexical frequencies to its form frequency, was computed for each heteronym. This provided a measure of the heteronyms' ambiguity level, with a higher frequency ratio indicating lower ambiguity in the word's meaning. In addition to this lexical property, a measure representing the heteronyms' form was also computed. This measure was based on those of open-bigram frequency, trigram frequency and word-form frequency (defined as the sum of each word's two lexical frequencies). The form measure was defined as the first component of a principal component analysis including these three variables, thus, in theory, encompassing the maximal co-variance of all three form-related properties. The resulting component, however, was primarily correlated with open-bigram and trigram frequencies, rather than with whole-word-form frequency—its coefficients were 0.70, 0.71 and 0.04, for open-bigram, trigram and whole-word-form frequency, respectively.

MEG data were analyzed using minimum-norm estimation, cortically constrained by each subject's structural MRI. Regions of interest were identified on a representative subject's cortical surface, based on heightened activation in the average minimum-norm solution across all subjects. All regions were then mapped onto individual subjects' brains, after which a trial-by-trial minimum-norm solution was computed for each region. Correlational analyses were conducted to examine the effects of the word-form and lexical properties of interest on the trial-by-trial activation, averaged across vertices within each selected ROI. In order to control for inter-subject variability, each subject's data were normalized into z-scores across trials prior to the cross-subject correlational analyses.

A positive peak in the average activation at about 190 ms post-stimulus onset was identified as the M170 response component. This activation was found bilaterally in the occipito-temporal fusiform gyrus area. Correlational analyses were conducted on positive activation in this region.[3] The left hemisphere region of interest identified for the analysis of the M170, along with the average time-course of positive activation in the region, is illustrated in Fig. 1. M170 analyses were conducted over a 50 ms window centered at each subject's M170 peak latency, with timing of activations defined relative to each individual subject's peak. A network of later, negative activation in the left hemisphere superior temporal and Sylvian Fissure areas was identified for analysis of the M350 component. This network showed heightened activation starting at the 250 ms range, followed by a peak in negative activity at about 330 ms. The region of interest identified by this activa-

[1] Heteronyms were mono-morphemic on at least one of the two possible readings.

[2] The group of control words was matched on its distribution over frequency to the entire group of frequency values for the target words, i.e. including the heteronyms' word-form and individual meaning frequencies.

[3] Positive activation indicates current flow outward from the cortical surface, while negative activation indicates current flow inward.

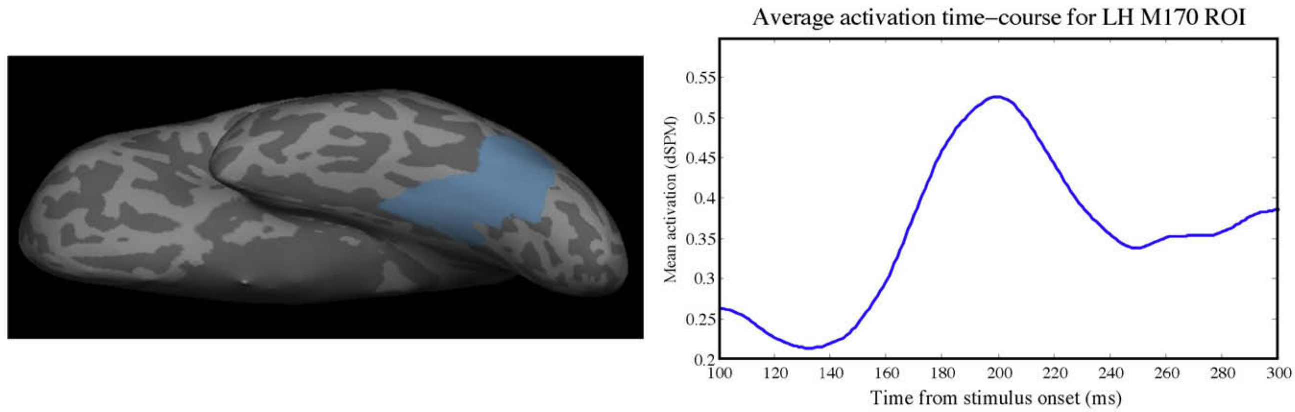

Fig. 1. Left hemisphere region of M170 activation, illustrated on a representative subject's inflated cortical surface, along with the average positive activity in the region across all trials and subjects.

tion, and the average time-course of negative activity in the region are illustrated in Fig. 2. Analyses of M350 activation were conducted over the 305–355 ms time window across all subjects (a 50 ms window centered at the 330 ms peak latency). Analyses of both components were conducted by computing correlations for each time-point within the larger time window of interest. Temporal clusters of consecutive significant effects identified in these time-course analyses underwent a correction procedure for multiple comparisons, based on the technique introduced by Maris and Oostenveld (2007).

The multiple comparison correction was performed by first defining a new statistic, $\sum r$, as the sum of all correlation coefficients within a temporal cluster of consecutive significant effects in the same direction (at the raw $p = 0.05$ significance level). A Monte-Carlo *p*-value was then computed, which indicated the statistical significance of the $\sum r$ statistic for each temporal cluster, given the multiple comparisons that gave rise to the effect. This *p*-value was computed as follows: the correlation wave was computed over time, as it had been in the original analysis, for 10,000 random permutations of the independent variable of interest. For each such randomly produced wave, the $\sum r$ statistic was computed for each temporal cluster, after which the highest absolute value of $\sum r$ was taken as the statistic for that permutation. This produced a distribution of 10,000 $\sum r$ values, to which the original value could be compared. The percentage of values higher in absolute value than the original statistic was taken to be the Monte-Carlo *p*-value for the original cluster.

3. Results

No significant differences were found between heteronyms and controls in behavioral response time or accuracy.

An analysis was conducted on M170 activation over a 50 ms time window centered at each subject's individual peak latency. A direct comparison of heteronyms versus controls revealed no significant effects in the left or right hemisphere M170 activity. Correlations were then computed between brain activity and both lexical and form properties of the presented words. There were no significant effects of heteronym frequency ratio on the M170 in either the left hemisphere or the right. There were also no effects of heteronym (low or high) or control frequency. A significant effect of the principal component measure of the heteronyms' form properties was found in the left hemisphere M170 region, starting 8ms after each subject's peak latency, and continuing for 16ms ($\sum r = 2.80$ for 16 time-points, $p < 0.05$ following correction for multiple comparisons). The time-course of this effect is illustrated in the left panel of Fig. 3. Right hemisphere M170 activity was not correlated with the form-property measure.

Correlations were computed between M350 activation over the 305–355 ms time range and the lexical properties of interest. No significant difference was found in the M350 response to heteronyms as compared to controls. Heteronym frequency ratio was found to have a significant inhibitory effect (i.e. significantly less negative activation) on M350 activity throughout the 325–339 ms range ($\sum r = 2.87$ for 15 time-points, $p < 0.05$ following

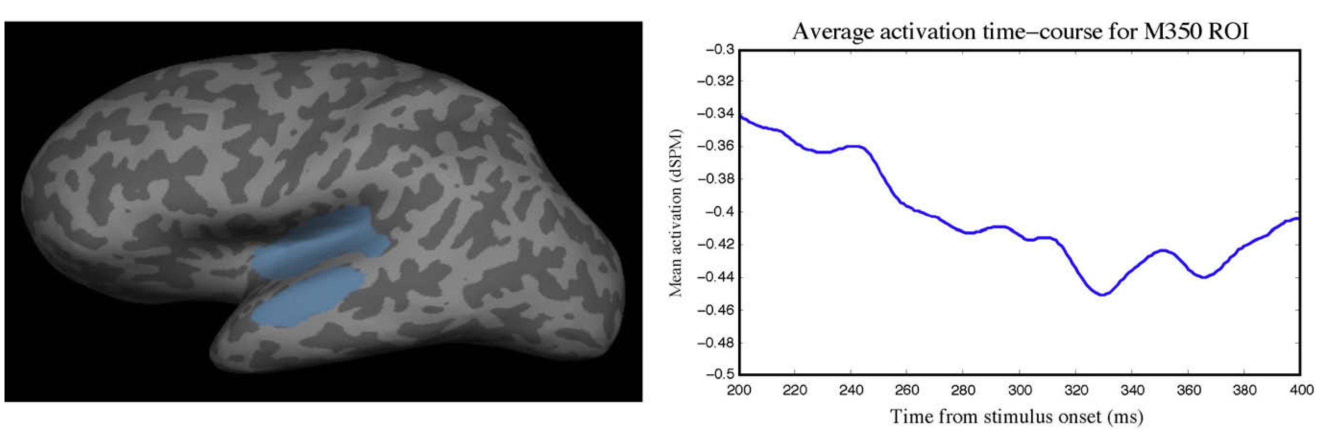

Fig. 2. Region of interest identifying network of M350 activation in the left hemisphere, illustrated on a representative subject's inflated cortical surface, along with the average negative activity in the region across all trials and subjects.

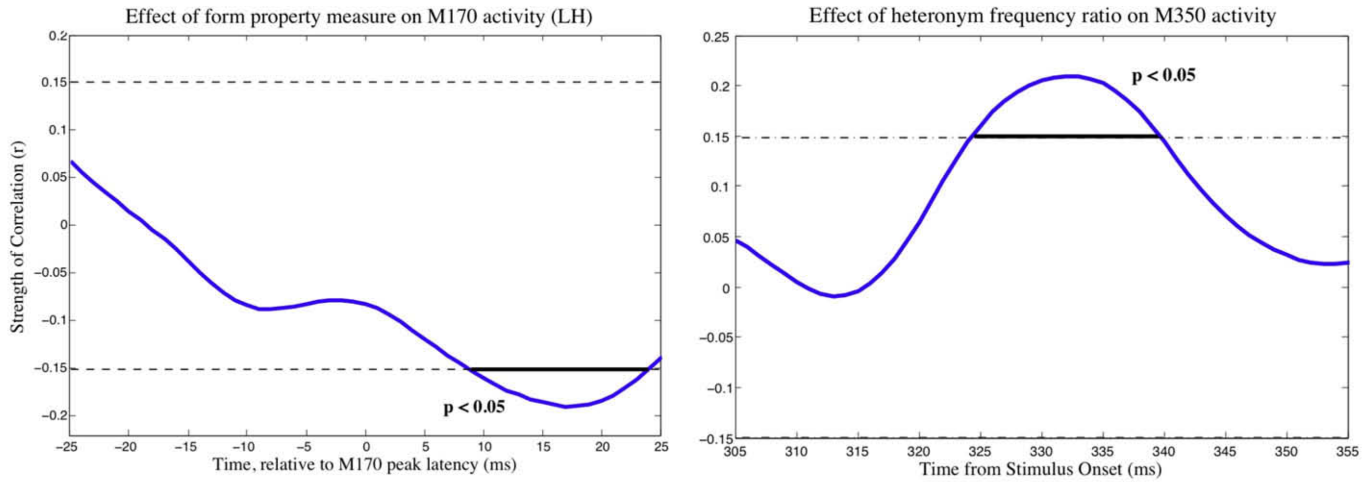

Fig. 3. Left: Effect of the form frequency measure in the left hemisphere M170 region. Right: Effect of the heteronym frequency ratio in the M350 region. Each correlation is plotted over time, with the $p = 0.05$ significance level (prior to correction for multiple comparisons) indicated by the dotted line. Bold lines identify temporal clusters subject to the Monte-Carlo correction procedure. Note that M350 activation is negative, so a positive correlation indicates an inhibitory effect.

multiple comparison correction). The time-course of this correlation is illustrated in the right panel of Fig. 3. Heteronym (low and high) and control word frequency had no effect on the M350. The form frequency measure also had no effect on M350 activity.

Exploratory time-course analyses were also conducted on activation in the 100–150 and 200–300 ms time windows, but these analyses revealed no significant effects.

4. Discussion

The current study was designed to shed light on the time-course of processing in visual word recognition. In particular, our aim was to distinguish between abstract word-form recognition and genuine lexical access, especially in early stages of processing. Examining visual recognition of heteronyms—phonologically and semantically distinct words that share a common orthography—provides a unique opportunity to distinguish between lexical and word-form properties.

We identified two components of visual word recognition in time and brain space—the M170 and M350—at which we examined brain activity in response to heteronyms. At the early processing stage of the M170, we found no effects of properties relating to the individual meanings of the heteronyms, particularly of the frequency ratio of one meaning to the other. The only significant modulator of left hemisphere M170 activity was a measure of the heteronym's form, encompassing open-bigram, trigram and whole-word-form frequencies. Only at the later stage of the M350 did we see any indication of higher-level lexical processing, as revealed by the effect of heteronym frequency ratio.

These results suggest that, contrary to the 'early lexical access' theory, words are not identified as lexical items in early stages of processing. Our results point to a model of word recognition in which the earlier M170 response is associated with the identification of abstract, orthographic word-form properties, while the later M350 response is concerned with the processing of higher-level lexical properties and access to the mental lexicon that connects the sound and meaning of words. The presence of a form-related effect at the M170, along with the insignificance of the heteronyms' lexical properties at this early stage in processing, suggests that the early frequency effects reported in the literature may be the reflection of abstract word-form identification rather than genuine lexical access. The heteronyms' true lexical properties do not become relevant until after 300ms post-stimulus onset, which is evidence to suggest that lexical access does not occur before this point.

We should emphasize that the null results reported here for possible early lexical influence on visual word formation need to be considered together with the experiments in the literature claiming early semantic effects on lexical access (Hauk et al., 2006; Penolazzi et al., 2007; Pulvermüller et al., 2001; Sereno, Brewer, & O'Donnell, 2003; Sereno et al., 1998). Many of these claims, however, rest at least in part on early effects of lexicality or frequency (Hauk et al., 2006; Penolazzi et al., 2007; Sereno et al., 1998). Both of these variables are highly correlated with word-form frequency, and their effects might in fact be attributable to word-form recognition rather than true lexical access. Sereno, Brewer, and O'Donnell (2003) and Penolazzi et al. (2007) report early effects of semantic contextual priming, but it is both likely and completely consistent with the hypotheses supported in these papers that semantic priming is also accompanied by activation of the associated word-form. It is thus not clear that the early priming effects must be attributed to semantic rather than word-form expectations. The early contextual priming effect for ambiguous words found by Sereno et al. (2003) is particularly difficult to interpret given its direction. Unlike unambiguous low frequency words, which were facilitated by a biasing context, ambiguous words were inhibited when primed with their subordinate meanings. This discrepancy prevents an entirely straightforward interpretation of the results. In any case, the authors did not consider alternative accounts of their data that would involve activation of the lexical entry for the dominant meaning of an ambiguous word via the word-form shared with the entry for the subordinate meaning when the subordinate meaning is semantically primed. The early effect of "semantic coherence" reported by Hauk et al. (2006) is also not completely straightforward. Semantic coherence in the study is based on the semantic relatedness among the members of a word's morphological family. The semantic transparency of a derived word, like "happiness" from "happy", has been linked to the decomposition of the word in processing and storage (see e.g., Hay & Baayen, 2005). The semantic coherence of the morphological family of a word, then, should be related to the activation of the visual word-form of the word when members of the family are encountered, with derived words that are more closely related semantically to a stem more likely to be tied to the visual word-form of the stem. We might therefore expect word-form frequency effects in early stages of visual word recognition to be modulated by the semantic coherence of a word's morphological family, as reported by Hauk et al. (2006). (See Zweig and Pylkkänen (2008) for a discussion of the evidence for early morphological decomposition in visual word recognition relevant to this issue.) Pulvermüller et al. (2001) report an early effect of semantic association but this result is limited to a single subject design with only four target stimuli for each of four semantic categories. In addition, the experimental paradigm involved memorization of the words and multiply repeated presentations. Overall, these findings do not argue strongly against the late access theory of visual word recognition, especially given the difficulty in distinguishing between word-form and semantic effects in the majority of situations. Heteronym recognition, in contrast, provides a clear case in which the theories make competing predictions.

The brain regions and patterns of activation identified in the current study are also consistent with a model of visual word recognition in which orthographic word-form properties are detected at the earliest stages of word identification, followed by semantic properties at later stages in processing. The M170 response was localized to the fusiform gyrus area, and corresponds to the "visual word-form area" identified by Cohen et al. as a region that responds to abstract orthographic properties of words (Cohen & Dehaene, 2004; Dehaene et al., 2002). Brain areas classically associated with linguistic processing did not show significant activation at this early stage. We should note that nothing in this discussion depends on the existence of a visual word-form area specialized for word recognition; the critical activity measured from the fusiform area in this experiment could be generated by either general or word-specific object recognition systems (Devlin, Jamison, Gonnerman, & Matthews, 2006; Price & Devlin, 2003).

In contrast to the early M170 response, the later activation of the M350 was localized to superior temporal regions more typically associated with language. This superior temporal network is likely involved in activation of lexical entries and choice among activated representations, as is suggested by the relevance of the heteronym frequency ratio. The effects of heteronym frequency ratio also make sense in the context of the time-course generally associated with word recognition. Given the consensus in the ERP and MEG literature that lexical access happens no later than 350–400 ms, the choice of a match for a target heteronym from two separate lexical entries should be completed by about this time (Friederici, 2002; Hagoort, 2008).

The correlational analysis technique employed in the current study is of particular relevance to the results reported here. As the heteronyms used in the experiment were not chosen randomly, but rather comprise the full set of stimuli from English that were usable for our purposes, they do not represent an unbiased sample. Although the control words were matched to the heteronyms on various measures, the imbalance of the stimuli, with the controls randomly chosen from a large set within certain parameters and the heteronyms constituting the entire population of a particular corner of the English lexicon, prevents the direct comparison of the heteronyms versus the controls from being fully compelling. For this reason, we primarily focus on the effects of properties that vary within the group of heteronyms themselves, such as the frequency-ratio measure. The correlational analysis method is a way to test the effects of continuous variables of interest such as this without any binning of the stimuli. As discussed earlier, this technique is useful for analyzing linguistic data in general, as the properties of actual words in any particular language are not always or even usually balanced with respect to experimental variables of interest. The attempt to simultaneously control for multiple variables often results in very limited candidate stimuli for bins in a factorial design, making random sampling virtually impossible. When some cells in a paradigm exhaust the potential stimuli from a language while others are filled by samples from a large set, standard assumptions behind inferential statistics may be violated (Baayen, 2004).

To summarize, the results of the current study elucidate the nature of visual word recognition as a process that begins with an early visual response to the orthographic properties of a word (the M170), followed by the later M350 response by which orthography is mapped to a particular lexical entry. The latter response component is localized to a region classically associated with language comprehension and seems to be involved in genuine lexical identification, as opposed to the purely abstract form identification that occurs at the stage of the M170. In particular, this model of visual word recognition would entail that, contrary to the 'early access' theory, true lexical access does not occur prior to 200 ms, but rather at a later stage in processing. This study also presents a correlational analysis method that can provide a means for further investigation of word recognition and other forms of neurolinguistic processing.

Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.bandl.2008.09.004.

References

Baayen, R. H., Piepenbrock, R., & Gulikers, L. (1995). *The CELEX Lexical Database (Release 2) [CD ROM]*. Philadelphia, PA: Linguistic Data Consortium, University of Pennsylvania.

Baayen, R. H. (2004). *Statistics in psycholinguistics: A critique of some current gold standards*. Mental Lexicon Working Papers I.

Cohen, L., & Dehaene, S. (2004). Specialization within the ventral stream: The case for the visual word form area. *NeuroImage, 22*(1), 466–476.

Cornelissen, P., Tarkiainen, A., Helenius, P., & Salmelin, R. (2003). Cortical effects of shifting letter position in letter strings of varying length. *Journal of Cognitive Neuroscience, 15*(5), 731–746.

Dehaene, S., Cohen, L., Sigman, M., & Vinckier, F. (2005). The neural code for written words: A proposal. *Trends in Cognitive Science, 9*(7), 335–341.

Dehaene, S., Le Clec, H. G., Poline, J. B., Le Bihan, D., & Cohen, L. (2002). The visual word form area: A prelexical representation of visual words in the fusiform gyrus. *NeuroReport, 13*(3), 321–325.

Devlin, J. T., Jamison, H. L., Gonnerman, L. M., & Matthews, P. M. (2006). The role of the posterior fusiform gyrus in reading. *Journal of Cognitive Neuroscience, 18*(6), 911–922.

Friederici, A. D. (2002). Towards a neural basis of auditory sentence processing. *Trends in Cognitive Science, 6*(2), 78–84.

Hagoort, P. (2008). The fractionation of spoken language understanding by measuring electrical and magnetic brain signals. *Philosophical Transactions of the Royal Society of London. Series B, Biological Sciences, 363*(1493), 1055–1069.

Hauk, O., Davis, M. H., Ford, M., Pulvermüller, F., & Marslen-Wilson, W. D. (2006). The time course of visual word recognition as revealed by linear regression analysis of ERP data. *NeuroImage, 30*(4), 1383–1400.

Hay, J., & Baayen, R. H. (2005). Shifting Paradigms: Gradient structure in morphology. *Trends in Cognitive Science, 9*(7), 342–348.

Marinkovic, K. (2004). Spatiotemporal dynamics of word processing in the human cortex. *Neuroscientist, 10*(2), 142–152.

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG- and MEG-data. *Journal of Neuroscience Methods, 164*, 177–190.

Pammer, K., Hansen, P. C., Kringelbach, M. L., Holliday, I., Barnes, G., Hillebrand, A., et al. (2004). Visual word recognition: The first half second. *NeuroImage, 22*(4), 1819–1825.

Penolazzi, B., Hauk, O., & Pulvermüller, F. (2007). Early semantic context integration and lexical access as revealed by event-related brain potentials. *Biological Psychology, 74*(3), 374–388.

Price, C. J., & Devlin, J. T. (2003). The myth of the visual word form area. *NeuroImage, 19*(3), 473–481.

Pulvermüller, F., Assadollahi, R., & Elbert, T. (2001). Neuromagnetic evidence for early semantic access in word recognition. *European Journal of Neuroscience, 13*(1), 201–205.

Pylkkänen, L., & Marantz, A. (2003). Tracking the time course of word recognition with MEG. *Trends in Cognitive Science, 7*(5), 187–189.

Sereno, S. C., Brewer, C. C., & O'Donnell, P. J. (2003). Context effects in word recognition: Evidence for early interactive processing. *Psychological Science, 14*(4), 328–333.

Sereno, S. C., Rayner, K., & Posner, M. I. (1998). Establishing a time-line of word recognition: Evidence from eye movements and event-related potentials. *NeuroReport, 9*(10), 2195–2200.

Tarkiainen, A., Cornelissen, P. L., & Salmelin, R. (2002). Dynamics of visual feature analysis and object-level processing in face versus letter-string perception. *Brain, 125*(5), 1125–1136.
Tarkiainen, A., Helenius, P., Hansen, P. C., Cornelissen, P. L., & Salmelin, R. (1999). Dynamics of letter string perception in the human occipitotemporal cortex. *Brain, 122*(11), 2119–2132.
Vinckier, F., Dehaene, S., Jobert, A., Dubus, J. P., Sigman, M., & Cohen, L. (2007). Hierarchical coding of letter strings in the ventral stream: Dissecting the inner organization of the visual word-form system. *Neuron, 55*(1), 143–156.
Zweig, E., & Pylkkänen, L. (2008). A visual M170 effect of morphological complexity. *Language and Cognitive Processes*, in press. doi:10.1080/01690960802180420.