



Does silent reading speed in normal adult readers depend on early visual processes? Evidence from event-related brain potentials

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ABSTRACT

Little is known about the relationship of reading speed and early visual processes in normal readers. Here we examined the association of the early P1, N170 and late N1 component in visual event-related potentials (ERPs) with silent reading speed and a number of additional cognitive skills in a sample of 52 adult German readers utilizing a Lexical Decision Task (LDT) and a Face Decision Task (FDT). Amplitudes of the N170 component in the LDT but, interestingly, also in the FDT correlated with behavioral tests measuring silent reading speed. We suggest that reading speed performance can be at least partially accounted for by the extraction of essential structural information from visual stimuli, consisting of a domain-general and a domain-specific expertise-based portion.

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1. Introduction

The quick and thorough processing of written information is a key skill in modern life. The speed at which a text can be read depends, first of all, on properties of the text. Thus, a number of reading models as for instance the Dual Route Model (Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001) or the Parallel Distributed Processing Model of Visual Word Recognition and Pronunciation (Seidenberg & McClelland, 1989) investigated word identification speed as depending on stimulus features like frequency, length, number of neighbors, or regularity. However, reading speed also depends on the reader. Most obviously, reading speed improves with skill acquisition but considerable individual differences remain even after extensive amounts of training. The most striking example is dyslexia, consisting in slow and laborious reading that may persist during adulthood. However, also in non-dyslexic readers there are large, yet underinvestigated individual differences in reading speed. The present study is concerned with the neurocognitive underpinnings of normal variability in reading speed. We show that at least some of the variance in the speed of reading performance can be attributed to the functioning of relatively early visual processes.

1.1. Silent reading speed and brain activity

The construct ‘reading speed’¹ in terms of an individual’s ability level can be seen as depending on numerous processes and sub-processes involved in reading like visual attention allocation (Brannan & Williams, 1987), working memory (Daneman & Carpenter, 1980), phonological processing (Shankweiler & Fowler, 2004), retrieval of word meaning from long term memory (Ericsson & Kintsch, 1995) and countless possible interactions of these sub-processes. Individuals may differ on any or all of these levels.

The vast majority of studies, which attempted to link reading performance to brain activity, have investigated extreme groups of readers as for instance dyslexic readers or patients with brain injuries as compared to regular readers or participants of various age groups (see for instance Shaywitz & Shaywitz, 2005). Fewer researchers have addressed individual differences within a normal population. Thus, studies which investigated reading performance among regular readers found differences in event-related brain potentials (ERPs) attributed to working memory processes

¹ In the context of this paper the term “reading speed” is used as a measure for the time needed to read and comprehend a text during silent reading. The more common term “reading fluency” is not applied because it could be associated with the absence of hesitations and incorrect pronunciations in oral reading. Although oral reading speed is a widely accepted indicator for reading performance this paper focuses solely on silent reading due to its higher ecological validity and importance within a sample of adult readers.

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(Bornkessel, Fiebach, & Friederici, 2004; Friederici, Steinhauer, Mecklinger, & Meyer, 1998; King & Kutas, 1995).

However, these studies focused on sub-processes, which are subsequent to and therefore dependent on visual processing stages. In contrast, the present study examines individual differences among adult readers with respect to early stages of visual perception and their impact on silent reading speed. An excellent tool to examine the time course of stimulus processing with millisecond precision is provided by ERPs. They allow the assessment of distinct cognitive sub-processes involved in language processing, which otherwise would be difficult or impossible to estimate in behavioral test paradigms. Cognitive sub-processes are reflected in separable components of the ERP. These components can vary in terms of amplitude and latency, reflecting, in turn, the intensity and timing of the corresponding processes. The main tools of the present study will be three components of the visual evoked potential, the P1, N170, and N1, to be shortly reviewed next.

1.2. P1 – attention allocation

The amplitude of the first positive deflection in the EEG, peaking in occipital regions about 100 ms after the presentation of a visual stimulus, the P1, exhibits a sensitivity to physical stimulus characteristics, for example, stimulus size, contrast and luminance (Kutas, Van Petten, & Kluender, 2006). The P1's sensitivity to attention allocation has been demonstrated in numerous studies (Hillyard, Teder-Sälejärvi, and Münte (1998), for a review). There is consensus that the P1 component is mainly generated in extra-striate visual areas (Di Russo, Martinez, Sereno, Pitzalis, & Hillyard, 2001).

Behavioral studies, which compared dyslexic and unimpaired readers, demonstrated a deficit among impaired readers in their ability to shift and maintain visual attention. This was discussed as a possible reason for their reading difficulty (Facoetti, Paganoni, Turatto, Marzola, & Mascetti, 2000; Facoetti et al., 2006). However, to our knowledge there are no studies, linking these difficulties to P1 sensitivity.

1.3. N170 – domain specific structural analysis

Based on its approximate peak latency Bentin, Allison, Puce, Perez, and McCarthy (1996) named the negative component succeeding the P1 over tempo-parietal scalp regions N170. Since in their experiments it was only elicited by face stimuli the authors assumed a face-specific function in perception. Subsequently N170 amplitudes were found to be larger in experts in a specific field of interest, e.g. birds, dogs, or cars, when looking at stimuli of their expertise; therefore, the N170 was also interpreted as reflecting visual expertise (Gauthier, Curran, Curby, & Collins, 2003; Tanaka & Curran, 2001). In addition, it was shown that N170 responses to faces were unaffected by face familiarity (Bentin & Deouell, 2000; Herzmann, Schweinberger, Sommer, & Jentsch, 2004). Thus the N170 was seen as reflecting structural analysis, a visual processing step prior to the engagement of memory representations of the face or semantic knowledge (Eimer, 2000).

In the field of reading research the comparability of findings concerning the N170 is somewhat limited. A number of labels (N1, N170, N160, N150, early and late N1) can be found in the pertinent literature. This inconsistency might be caused by variations in the temporal definition of the component. The overview in Table 1 illustrates that some researchers seem to define a rather early and narrow N1 component, others define the N1 in a broader time range going beyond 200 ms after stimulus onset, while a third group uses a twofold definition of the N1. For clarity's sake in this article a component defined for a time range unifying the early and later part will be named 'broad N1'. The term 'N170' describes a component limited to the 200 ms after stimulus onset; if present,

a subsequent component will be called 'late N1'. The labels 'face' and 'word' will differentiate between face and linguistic stimulus materials.

Relevant for reading research are findings that words, pseudowords, non-words, strings of alphanumeric symbols, and strings of non-orthographic stimuli all elicit a clear N170 (Bentin, Mouchetant-Rostaing, Giard, Echallier, & Pernier, 1999). However, orthographic and non-orthographic stimuli are processed differently, that is, the amplitude of the N170 for orthographic stimuli is larger over left temporo-parietal regions. Maurer, Zevin, and McCandliss (2008) showed that this laterality effect is driven by script familiarity, that is, unlike Japanese participants English monolingual readers confronted with Japanese characters showed a bilateral distribution of a broad N1. This left-dominant lateralization triggered by linguistic stimuli was replicated in numerous studies for the broad N1 (Brem et al., 2006; Maurer, Brem, Bucher, & Brandeis, 2005) as well as for the N170 (Maurer, Rossion, & McCandliss, 2008; Spironelli & Angril, 2009; Tarkiainen, Cornelissen, & Salmelin, 2002).

Different brain responses for words and pseudowords observed by some researchers during the time window of the N170_{word} (Hauk & Pulvermüller, 2004; Sauseng, Bergmann, & Wimmer, 2004; Sereno, Rayner, & Posner, 1998) were interpreted as an indicator of lexical access. However, others reported an absence of lexicality effects in this component, that is, words and pseudowords elicited similar brain activation patterns (Bentin et al., 1999; Maurer et al., 2005; Wydell, Vuorinen, Helenius, & Salmelin, 2003). An absence of lexicality effects is in accord with a pre-semantic function of the N170 proposed in face perception studies (Bentin & Deouell, 2000; Herzmann et al., 2004; for recent review see Eimer, 2011). Hence, although results for the N170_{word} are inconsistent; a function of 'visual structure analysis' for face and word perception as proposed already by Schendan, Ganis, and Kutas (1998) seems plausible.

Since only few researchers divided the broad N1 into two segments, little is known about the distinct function of the late N1 component. Simon, Bernard, Largy, Lalonde, and Rebai (2004) found that pronounceable pseudowords elicited larger late N1 amplitudes than consonant strings. Based also on their source localization results (left mid-temporal gyrus) the authors postulated that the late N1 is associated with lexical retrieval of a phonological nature. Source localization results of Brem et al. (2006) indicate the involvement of broad regions from the left parahippocampal gyrus to fusiform, infero-temporal, and middle-temporal gyri. Because of the proximity to the source to the Visual Word Form Area (discussed below) the authors concluded that the late N1 reflects the activation of this brain region. Still, the exact function of the late N1 remains unclear.

To our knowledge the only study of visual processing comparing nonimpaired participants with different levels of language proficiency, reported a weak relationship with an N1 component (Weber-Fox, Davis, & Cuadrado, 2003). Note that although Weber-Fox and colleagues also reported N170 data for rather unusual scalp positions (O1, O2), the scalp location (CP4) and time range (50–190 ms) of their N1 fits N170 definitions as used in the present article. Amplitudes of the N1 were larger for a high proficiency group, but regression analyses between the peak amplitudes and proficiency scores did not reveal a significant relationship.

Developmental studies indirectly link levels of reading proficiency to brain activity in N170/broad N1 time segments but also disclose the impact of maturation. In general, stronger and delayed brain responses for children as compared to adults have been found for the initial steps of visual stimulus processing (Brem et al., 2009; Grossi, Coch, Coffey-Corina, Holcomb, & Neville, 2001; Maurer et al., 2006). The impact of text exposure on brain activity becomes visible already very early. According to Maurer

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