Dorsal stream associations with orthographic and phonological processing

Kristofer Kinsey[a], Peter C. Hansen[a,b] and Christopher H. Chase[c]

[a]University Laboratory of Physiology, Oxford University, Oxford, [b]School of Psychology, Birmingham University, Birmingham, UK and [c]Department of Psychology, Claremont McKenna College, Claremont, California, USA

Correspondence and requests for reprints to K. Kinsey, PhD, University of Oxford, Parks Road, Oxford OX1 3PT, UK
Tel: + 44 1865 271444; fax: + 44 1865 272469; e-mail: kris.kinsey@physiol.ox.ac.uk

Several studies have indicated a key role for dorsal stream processing in lexical decoding. To examine this relationship further, performance on orthographic and phonological reading tests was compared with both steady-state visual evoked potentials and a putative behavioral measure of dorsal stream processing, coherent motion detection. Frequency analysis of the visual evoked potential data showed power at the second harmonic to be largely confined to dorsal stream regions, and significantly correlated with motion detection thresholds. Regression analyses showed that orthographic processing was significantly associated with the second harmonic power. Although consistent with previous reports, there remains a question as to why the orthographic visual evoked potential power relationship did not extend to include the coherent motion detection measures. *NeuroReport* 17:335–339 © 2006 Lippincott Williams & Wilkins.

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Introduction

For skilled readers processing familiar words, visual recognition of each word is thought to operate automatically, with semantic meaning being directly accessed from the orthographic lexicon at the whole word level. The need also arises to decode lexical strings that are unfamiliar as well as familiar. For such unfamiliar words, one must adopt a strategy whereby the visual components of the text are segregated and processed independently before being combined with the appropriate phonological codes to either access or generate a semantic representation. In this dual route model of reading [1], it has been argued that orthographic processing is mediated by a network of posterior brain structures extending upward from the visual cortex, hereafter referred to as the dorsal visual stream [2]. Several issues, however, are raised by this hypothesized relationship. Foremost, there is a lack of experimental consistency to support the argument that dorsal stream processing is strongly associated with any one particular reading route (as defined in the dual route reading model). The source of this discrepancy awaits further elucidation. In the current study, we further explore the relationship between orthographic and phonological processing and the dorsal stream using methodologies that both replicate and extend previous research.

Evidence suggests that the occipitoparietal system or dorsal stream operate in a way that aids stimuli localization in the field of view [3]. Anatomically, the dorsal stream represents a collection of brain regions that extend upwards from the primary visual cortex (V1) towards the middle temporal area (MT/V5) and terminate in the parietal cortex.

The stream is fed by information carried in segregated processing pathways projected from the retina. Much of the dorsal stream activity stems from information carried by the fast transmitting magnocellular pathway; however, contributions are made by other retinocortical pathways such as the koniocellular pathway [4].

In recent models of reading, there is a specific emphasis on the role played by the magnocellular pathway and the dorsal stream. In one such model, the magnocellular pathway quickly transmits a portion of the visual input up the dorsal stream to parietal regions where a spatial code is generated. This information is quickly transmitted back to the visual cortex and aids decoding of the remaining input primarily carried by other slower transmitting visual pathways [5]. In another model, the magnocellular system is thought to be able to encode text directly [6]. Here, the portion of the visual input carried by the magnocellular pathway acts to prime lexical recognition regions. In cases in which the orthographic form is well known, access to semantic representations may be gained directly.

The study of developmental dyslexia has stimulated considerable research into a possible relationship between visual and lexical processing. Results from several studies have led to a proposal of a specific magnocellular deficit hypothesis underlying the development of dyslexia [7]. Experimental support for the magnocellular deficit hypothesis, however, remains controversial. In part, this is because of the hypothesis' inability to account for the range of sensory processing abilities observed in dyslexia. Many of the criticisms of this hypothesis, however, have been leveled at methodologies used to identify processing specific to

a subcortical processing route such as the magnocellular pathway [8].

In part, methodological differences between studies including task selection and participant characteristics may have contributed to the discrepant reports of associations between visual and lexical processing. With regard to task selection, specific reference to activation in the magnocellular pathway or the dorsal stream has been cited. The range of stimuli used in these studies, however, activates a large neural network and to say that any one stimuli type limits neural activation to a specific component within the network is perhaps too simplistic. Therefore, it is possible that previous studies have characterized unique aspects of visual processing, such as visual attention shifting [9], to which reading ability may be differentially associated. Similarly, with regard to participant selection, there has been great variation between studies. As noted above, several studies have examined visual processing associated with dyslexia but there continues to be contention regarding the criteria used to define the dyslexic population. While some state the group represents a unique population with subtypes [10], others suggest that dyslexia simply represents the lower end of a normal distribution of reading abilities [11]. Some studies have included both child and adult populations. Others have examined typically developing individuals grouped by reading ability. These methodological differences make accurate comparisons between studies particularly troublesome.

In the current study, we examine sensory and reading ability in a group of skilled adult readers. For our measure of dorsal stream activity, we selected both a coherent motion detection task and a visual evoked potential (VEP) measure. As such, we attempt to replicate results from previous studies and to extend our findings to include a more direct measure of neural processing.

Materials and methods
Participants
Thirteen young adults were recruited from the Claremont Colleges and the Claremont Unified school district (mean age=18 years, SD=1.9). All participants were at least 15 years of age, had a reading age score of secondary school or above as determined by the Wide Range Achievement Test [12], had normal to corrected vision, and had no history of cognitive problems or learning disabilities.

Coherent motion
Stimuli
Stimuli consisted of two random-dot kinematogram patches [13]. Patches were composed of 300 high luminance white dots, 1 pixel in size, moving $7°/s$ on a black background. The sizes of the patches were $10° \times 10°$ of the viewing angle with $5°$ of separation. The coherent dots moved leftwards or rightwards and changed direction every 860 ms. The noncoherent dots moved randomly in a Brownian manner. Each dot had a fixed lifetime of 86 ms and participants focused on a fixation dot located between the two random-dot kinematogram patches.

Procedure
In each trial, participants indicated the patch in which coherent motion was perceived. The percentage of coherently moving dots within a given trial (2300 ms duration)

was increased or decreased depending on the response accuracy on the previous trial. The threshold or percentage of coherent dots needed to perceive the direction of motion was determined by taking the geometric average of the last eight of 10 points where a percentage increase was followed by a decrease or vice versa. The procedure was repeated twice and a final threshold was determined by taking the mean of the two.

Visual evoked potentials
Stimuli
Visual stimuli consisted of achromatic 0.5 cycles per degree square wave gratings subtending $3° \times 3°$ of the viewing angle presented at 12cd/m^2 (± 1). Contrast alternating gratings were presented using Superlab software (Cedrus, San Pedro, California, USA) at a 9.5 Hz rate and remained visible for 850 ms.

Apparatus
A 32-channel electrode cap referenced to the right mastoid was used where eye movements were detected and rejected from analysis via two prefrontal electrodes if amplitudes reached $\pm 75 \mu$V. Signals were routed through a 30-gain DC head box into a SynAmps amplifier with a band-pass of 0.15–100 Hz set to a gain of 500 (both NeuroScan Incorporated, El Paso, Texas, USA). One hundred sweeps were digitized at a rate of 1000 Hz and recorded using Scan 4.1 software (NeuroScan Incorporated). Impedance, on average, was kept below 5 kΩ for each electrode.

Psychometrics
Orthographic processing task
Orthographic processing was assessed by presenting participants with 53 sets of two phonologically identical letter strings arranged one above the other on the monitor (e.g. ski/skee, soap/sope). Participants identified the position of the real word. Reaction times and errors were recorded for each trial. Presentations were ordered such that a premask (xxxx/xxxx) appeared on the screen for 1000 ms followed by the letter strings. Immediately after a response was given, the premask appeared.

Phonological processing tasks
Phonological awareness, phonological memory and rapid naming were assessed using the Comprehensive Test of Phonological Processing [14]. Phonological awareness was determined by performance on the Elision and Blending Words subtests. The Elision test requires participants to listen to and repeat compound words. In the word-blending task, the examinee listens to an audiocassette of separated word sounds and produces the combined sounds. Phonological memory was measured by the subtests Memory for Digits and Nonword Repetition. Lastly, both speed and error rates for naming digits and letters were calculated to determine the rapid naming ability.

Participants were also given a reading task developed by Coltheart and colleagues [1]. The task has been used extensively to screen for readers who have phonological or orthographic processing difficulties. Thirty pronounceable nonwords (e.g. bim) were given to measure grapheme to phoneme conversion skills and 30 irregular words (e.g. island) to measure direct access to the mental lexicon. Regular words were presented for comparison. Participants

were instructed to read the letter strings aloud. SuperLab software measured voice onset latency, and the experimenter recorded pronunciation errors.

Results

A frequency analysis was used to examine the neurological activity associated with the 9.5 Hz square wave grating stimulus. At low spatial frequencies, activation to contrast reversing stimuli is composed of even harmonics of the fundamental frequency and low spatial frequencies carried in the magnocellular pathway exhibit a prominent second harmonic [15]. Therefore, in addition to the principal component, we examined second harmonic amplitudes to gauge magnocellular activity. Log transformations were used to normalize skewed frequency distributions. Activity at the principal component was distributed throughout the brain; however, the second harmonic seen at 19 Hz was primarily confined to posterior regions.

For the coherent motion task, the average threshold or percentage of dots needed to be moved coherently in order to detect motion direction was 6.7% (SD=3.1). A significant correlation was found between an individual's motion detection threshold and the amplitude of their second harmonic ($r=-0.686$, $P<0.05$), indicating that greater VEP activation at this harmonic was linked with lower coherent motion thresholds (see Fig. 1). No association, however, was found between coherent motion detection, reading ability or the principal frequency component at 9.5 Hz.

Multiple regression analyses were conducted to examine electrophysiological measures of dorsal stream activity and reading ability. A significant relationship was found between orthographic processing and the second harmonic VEP measure. One analysis included two measures of phonological processing ability (phonologic awareness and nonword reading). The second analysis included two measures of orthographic processing ability (lexical decision
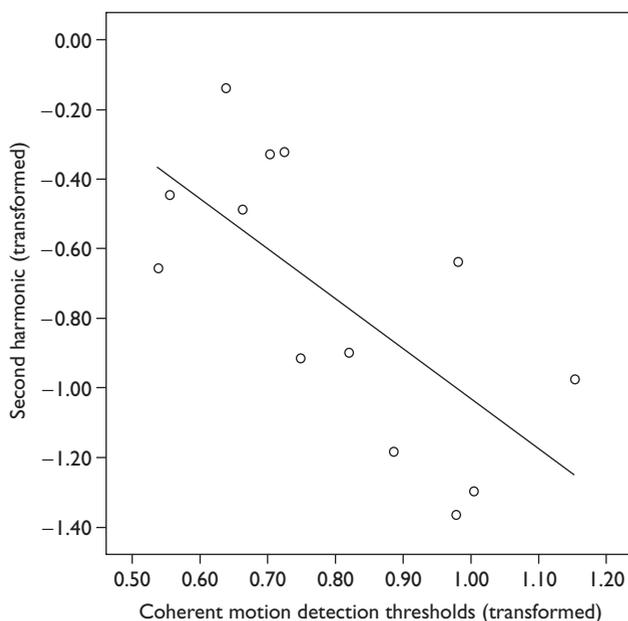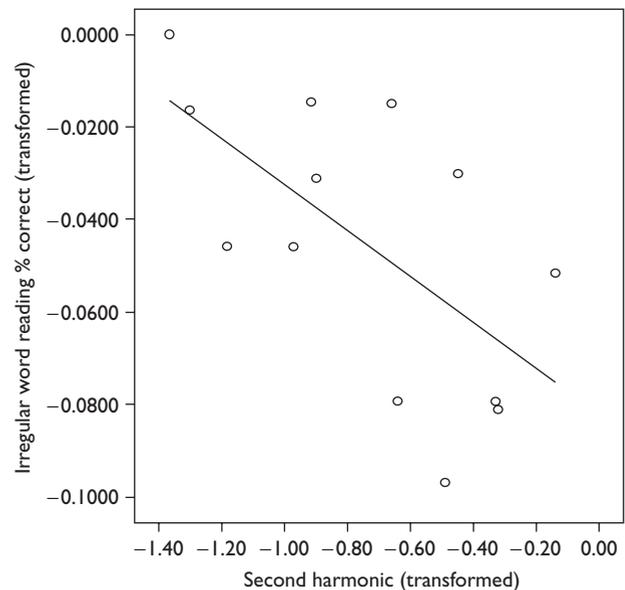

Fig. 2 Scatter plot showing the relationship between irregular word reading percentage correct and the measure of the second harmonic from the visual evoked potential task.

and irregular word reading). The regression equation with the phonological measures was not significant [$r^2=0.11$, adjusted $r^2=-0.08$, F(2,9)=0.58, $P=0.58$]. The regression equation with the orthographic measures, however, was significant [$r^2=0.58$, adjusted $r^2=0.48$, F(2,9)=6.10, $P=0.02$].

Next, a multiple regression analysis was conducted with all four reading measures as predictors. The linear combination of the four reading measures was not significantly related to the second harmonic [$r^2=0.80$, adjusted $r^2=0.45$, F(4,7)=3.20, $P=0.09$]. The orthographic measures predicted significantly over and above the phonological measures [r^2 change=0.53, F(2,7)=5.28, $P=0.04$]. The phonological measures, however, did not predict significantly over and above the orthographic measures [r^2 change=0.07, F(2,7)=0.69, $P=0.53$], indicating that the second harmonic function related to orthographic processing. Of the orthographic measures, percentage correct on the irregular word reading task was most strongly related to second harmonic functioning showing a bivariate correlation between irregular word reading and the VEP second harmonic ($r=-0.70$, $P<0.05$) (see Fig. 2). On the basis of these results, phonological reading ability appears to offer little predictive power of the second harmonic function compared with orthographical reading ability.

Discussion

Support for a specific functional relationship between dorsal stream processing and reading was mixed in this study. The behavioral measure on the basis of coherent motion detection did not show a significant relationship with either phonological or orthographic reading ability. In contrast, a component of the VEP measure primarily capturing dorsal activity did show a strong association with orthographic processing. While it is somewhat difficult to interpret these results, it is important to consider the particular characteristics of the methodologies used to gauge dorsal stream

Fig. 1 Scatter plot showing the relationship between the measures of the second harmonic from the visual evoked potential task and measures of the coherent motion thresholds.

function. Both approaches have been used in previous studies; however, the level of processing and the susceptibility to extraneous cognitive influences differ between the two.

Of the approaches used to characterize function in the dorsal stream brain regions, electrophysiological or VEP procedures have several advantages over other behavioral measures of the neural substrate. As a function of scale, VEPs represent more localized function. Here, the evoked responses stem from populations of neurons confined primarily in the visual cortex. Activation profiles of these neurons can further be characterized as sustained and transient responses. Stimulus onset activation is found in both activation profiles; however, in the sustained group, the peaks at each reversal are weakly defined compared with transient signals. A Fourier analysis of the waveforms, therefore, will show a fundamental component composed of both response types, whereas the second harmonic will be dominated by the transient response [15]. Within subjects, these stimulus-driven responses can be replicated over time and are resistant to momentary lapses in concentration.

Coherent motion detection thresholds, however, represent a more global index of dorsal stream function. Lesion [16], imaging [17] and electrophysiological studies [15] including these current findings support the notion that processing of random-dot kinematogram stimuli makes a particular demand on dorsal brain regions. The task, however, requires a perceptual judgment that is susceptible to a number of extraneous cognitive factors. Intersubject and intrasubject variability therefore is more capricious. For example, both task familiarity and attentional modulations can greatly affect detection thresholds. In the current task, detection thresholds were based on the average of two blocks of trials given one after the other. Pilot studies showed that participants improved in their detection ability over repeated blocks and then showed substantial levels of variability as fatigue began to set in. The learning curves and the point of fatigue were variable between participants. Determining a true measure of individuals' threshold was therefore rather unrealistic. Moreover, it has been shown previously that detection thresholds are much influenced by directing attentional resources [9] and can change because of simple lapses in concentration or vigilance [18].

In general, the findings in this study do support previous reports of a relationship between lexical and dorsal stream processing as evident from the link found between our VEP measure and irregular word reading. More specifically, these results are consistent with previous reports that a visual temporal processing component underlies aspects of orthographic decoding. For example, a group of skilled adult readers, similar to the participants examined in the current study [19], demonstrated that responses to 12 Hz flicker frequencies were highly correlated with irregular word reading. Moreover, this relationship could not be explained by reading style, defined by an individual's relative strength in either orthographic or phonological decoding.

It is difficult to determine the underlying operations that link both orthographic and dynamic visual processing. One hypothesis suggests that quick and accurate visual form processing is needed to read irregular words. It is the magnocellular and subsequent dorsal stream processing that most likely generates the speeded function needed [20]. Nonword reading on the other hand does not place as much demand on quick visual recognition but rather depends more on auditory temporal processing [19]. A dorsal stream processing component may, however, play a significant role in nonword reading. While this brain region shows specialization for processing transients, which may account for the speeded recognition needed for irregular word reading, function is also specialized for processing visual spatial shifts of attention [5]. The ability to shift visual attention in a speeded and accurate fashion aids in the rapid serial letter position encoding needed to add the phonological codes to nonwords [9].

Conclusion

The results from this study do support previous findings that dynamic visual processing associated with dorsal stream brain function does have a specific relationship with orthographic decoding as defined by the dual route model of reading. A qualification of this relationship does, however, appear to be in order. The mixed findings shown here highlight that the association may be contingent on certain methodological conditions. Given the range of functions performed by dorsal stream brain regions, task specificity can emphasize different processing components. Further research is therefore needed to characterize the relationship between dorsal stream activity and lexical processing. Specifically, research utilizing more direct measures of the cortex is needed.

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