An Event-Related Potential study of the relationship between N170 lateralization and
phonological awareness in developing readers

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RUNNING HEAD: Phonological awareness and the N170

Abstract

As reading development progresses, the visual processing of word forms becomes increasingly left-lateralized. This is visible, among other ways, as increased left-lateralization of the N170 ERP component. A primary explanation of this effect, the *phonological mapping hypothesis*, proposes that the left-lateralization of visual word form processing that accompanies reading development is the result of calling upon left hemisphere auditory language regions to perform the linking of orthography with phonology (phonological mapping). A key, but untested, prediction of the phonological mapping hypothesis is thus that individuals with greater phonological awareness should exhibit more left lateralized visual processing of word forms than individuals with poorer phonological awareness. We set out to test this hypothesis here. We accomplished this by collecting ERPs while children grades 5 - 6 viewed words, objects, and word/object ambiguous items (e.g., "SMILE" shaped like a smile - hereafter referred to as *wobjects*). Results revealed that, consistent with the phonological mapping hypothesis, individual phonological awareness (but *not* other measures of reading development) predicted left-lateralization of the N170 component elicited in response to words (but *not* item types that were not word-like).

Keywords: Event-Related Potentials, Phonological Awareness, Phonological Mapping Hypothesis, Individual Differences, Visual Word Recognition

1. Introduction

Reading is not an innate skill, and, indeed, only develops after years of explicit instruction. Prior to the onset of reading instruction, normally developing children already are able to link sounds (phonology) with meaning (semantics; see review in Harm & Seidenberg, 2004); key components of what must be learned during reading instruction, then, are how to 1) represent orthography (e.g., how to recognize letters and distinguish between them) and 2) make linkages between the new orthographic representations and existing phonological and semantic representations (extensive review in Harm & Seidenberg, 2004). Of course, this cognitive development is accompanied by brain development, with functional brain organization changing during the course of reading instruction to support the new representations and linkages that are being acquired (see, for example, Coch & Meade, 2016; Maurer & McCandliss, 2007). One hallmark of the neural re-organization that accompanies reading acquisition is an increased left-lateralization for the higher visual processing of text (e.g, Maurer, Brem, Bucher, & Brandeis, 2005; McCandliss, Cohen, & Dehaene, 2003; Maurer, Blau, Yoncheva, & McCandliss, 2010). This phenomenon is typically explained by the *Phonological Mapping Hypothesis*, which argues as follows: (1) phonological processing, even before the onset of reading acquisition, is typically left lateralized (Price, Moore, Humphreys, & Wise, 1997); (2) the left-lateralization of phonological processing is likely driven by the fact that auditory language comprehension and production centers are found in the left hemisphere (review in McCandliss & Nobel, 2003), and thus (3), when, during reading instruction, it becomes necessary for children

to learn to map orthography onto phonology, this process is more efficient in the left hemisphere, given (1) and (2), resulting in left-lateralization of print processing (find review of the Phonological Mapping Hypothesis in Maurer & McCandliss, 2008).

One prediction of the Phonological Mapping Hypothesis, as formulated above, is that, the greater a child's phonological awareness, the greater should be that child's left lateralization for print processing (as also argued in Maurer & McCandliss, 2008). This prediction reflects the proposition that the left hemisphere becomes involved in print processing to the extent that a child has begun to master phonological mapping. This prediction, to our knowledge, has not been tested directly in individual children in the literature. The goal of the present study is to test this prediction directly, in a group of children ages 10 - 12. We will ask whether an individual child's phonological awareness, as measured by the phonological awareness sub-component of the CTOPP-2, is predictive of the extent to which their electrophysiological response to print is left-lateralized. In particular, we will examine the lateralization of the N170 component of the Event-Related Potential (ERP), which we review next.

1.1. The N170

The N170 (sometimes also referred to as the visual N1) is a negative-going component of the ERP that is maximal around 170 ms post stimulus onset at a narrow range of lateral occipital electrode sites (see, for example, Rossion Joyce, Cottrell, & Tarr, 2003). The functional significance of the N170 is thought to be the "organization of visual cues into structured patterns" (Rossion & Caharel, 2011, p. 1308). In the case of visual word recognition, this function likely consists at least in part of linking visual features of print with more abstract orthographic features (Grainger & Holcomb, 2009;

Coch & Meade, 2016; see also Stites & Laszlo, Under Review), which are subsequently linked with lexical representations, likely mediated by phonology (Grainger & Holcomb, 2009; Eddy, Grainger, Holcomb, & Mitra, 2014). Consistent with this proposed function, the principal generators of the N170 have been localized to the occipitotemporal (OT) cortices (Rossion & Jacques, 2012). The N170 elicited in response to text tends to be left-lateralized in literate individuals (e.g., Rossion et al., 2003), but this left-lateralization is not observed in pre-literate children (Maurer et al., 2005).

It is clear that the N170 response to text does become more left-lateralized with reading experience (e.g., Maurer et al., 2011; Maurer et al., 2006; Laszlo & Sacchi, 2015; Brem et al., 2010). However, it is not clear whether this shift is directly related to improved phonological ability, *per se*, as would be predicted by the phonological mapping hypothesis, or is more diffusely related to improved reading ability. Is the increase in left-lateralization of the text N170 in better readers *only* related to their stronger phonological abilities, or is it *also* related to other verbal abilities, such as vocabulary skill? This is the primary question we will ask here. The phonological mapping hypothesis would predict that phonological awareness should impact the left-lateralization of the N170 in response to text, while vocabulary should not, as increased vocabulary ability does not necessarily call upon the left hemisphere auditory language regions that increased phonological ability does. Increased vocabulary skills could, for example, be more likely to call on the type of direct (not phonologically mediated) pathway between orthography and lexical-semantics that is proposed in numerous prominent reading models (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001;

Harm & Seidenberg, 2004). Support for the prediction that N170 left-lateralization is specifically related to phonological ability comes from results suggesting that phonological interventions increase left occipitotemporal activation in struggling readers (Shaywitz et al., 2004); similarly, phonological training in an artificial language increases left OT activation in adults (Xue, Chen, Jin, & Dong, 2006). Prior research does suggest that within the left OT cortex, greater activation in response to letter strings is associated with greater phonological ability (Parviainen, Helenius, Poskiparta, Niemi, & Salmelin, 2006)-- however, this work did not contrast left OT activation with right OT activation, so it does not specifically address, as we will, whether left *lateralization* is associated with greater phonological ability, or whether, instead, greater phonological ability is associated with greater OT activation generally.

The alternative hypothesis would be that increased verbal ability, by any metric, increases the left-lateralization of the N170. Evidence for this alternative hypothesis is drawn from past results suggesting that it is reading fluency and semantics, not phonological ability, that best predict the development of tuning (though not necessarily lateralization) for print on the N170 (Eberhard-Moscicka, Jost, Raith, & Maurer, 2014). We will examine this hypothesis by including phonological awareness and vocabulary skills (along with age) as simultaneous predictors in a mixed effects regression model with N170 left-lateralization as the outcome variable. By including multiple predictors of verbal development in the same model, we will be able to determine whether any effect of phonological awareness on N170 amplitude is specific to phonological awareness, or more broadly related to improved verbal development more generally.

The pattern of N170 lateralization typically observed for other types of visual stimuli is distinct from that for words. In particular, the face N170 tends to be right lateralized (e.g., Rossion et al., 2003), while the N170 response to visual objects tends to be bilateral (Rossion et al., 2003). If we observe an increased left-lateralization of the N170 in response to text with greater phonological ability, as would be predicted by the phonological mapping hypothesis, a second question we will ask here, then, is to what extent this relationship is specific to words, rather than generally observed across increasingly less-wordlike types of visual stimulation. In particular, we will examine N170 responses to visual objects, and also to a novel class of stimuli that are visually intermediate between words and objects, which we will refer to as *wobjects*. Sample wobjects (along with sample word and object stimuli used here) are provided in Figure 1. Each wobject is a vector drawing of a word, shaped to resemble the object that that word represents, for example, the word HEART shaped like a heart. We predict that the relationship between phonological awareness and increased left-lateralization of the N170 will only be evident to the extent that the eliciting stimulus is visually word-like. Thus, we might expect, for example, a strong relationship between phonological awareness and N170 left-lateralization for words, a weaker relationship for wobjects, and no relationship for objects.

As described, our experimental design will allow us not only to ask whether the N170 becomes more left-lateralized in response to print with increased phonological ability, but also whether this pattern, if observed, is 1) specifically driven by phonological ability and not other, related, skills and 2) specific to the processing of visual word forms, and not a more domain-general tuning of the higher visual system.

1.2 N170 Response to Wobjects in Adults (Laszlo & Sacchi, 2015)

In prior work, we have examined the N170 response of adults to these same items in this same task (Laszlo & Sacchi, 2015). The principal result of that study was that less experienced readers tended to display less differentiation between words, wobjects, and objects on the N170. A clear interpretation of this result is that, with reading experience, cortical representation of words becomes more distinct from cortical representations of other types of visual stimuli. A second, possible, interpretation, however, is that individuals who are less able to differentiate words from other visual stimuli, are less likely to seek reading out (because, for example, it is more effortful). With only a single developmental data point (that is, the data from adults), it is not possible to adjudicate between these two possibilities. A secondary motivation for the present study, therefore, was to evaluate whether this same pattern of activity found in adults (i.e., less differentiation between words, objects, and wobjects) is replicated in a developmental population. If observed, this would suggest that, minimally, it does not take an entire decade of reading expertise to develop strong patterns of differentiation between word forms and other decreasingly word-like stimuli (i.e., wobjects and objects). This result seems likely, as substantially less training, within the domain of text, at least, can impact the lateralization of the N170 (e.g., Yoncheva, Wise, & McCandliss, 2015). Alternatively, of course, we could observe equal N170 differentiation for words in children of both high and low ability. This would suggest that the pattern of de-differentiation displayed by adults with less reading experience is likely a *result* and not a *cause* of that lack of reading experience.

2. Methods

2.1. Participants

Data were collected from 20 children in grades 5 and 6 (10 female; mean age 11; age range 10-12). Within the sample, 10 children were in 5th grade (mean age 10.9, $\sigma = .74$) and 10 children were in 6th grade (mean age 11.1, $\sigma = .74$). All children were right-handed, reported no history of neurological disease or defect, and had normal or corrected-to-normal vision. All children reported being native, monolingual speakers of English, with no other languages being spoken in home or at school. No children reported any diagnosed learning disabilities. The Internal Review Board of Binghamton University approved all experimental procedures. Written permission to participate in the study was provided from each child's guardian, and children provided informed written assent as well as ongoing verbal assent throughout the experiment. Children were recruited via newspaper advertisements, radio advertisements, and word of mouth. Children were compensated with \$50 or a toy of equivalent value.

2.2. Behavioral assessments

Phonological awareness and vocabulary were assessed via standardized instruments. Phonological awareness was measured as the phonological awareness composite of the Comprehensive Test of Phonological Processing, 2nd edition (CTOPP-2; Wagner, Torgesen, Rashotte, & Pearson, 2013; see also Torgesen, Wagner & Rashotte, 1999). The phonological awareness composite includes the elision, blending words, phoneme isolation, rapid digit naming, and rapid letter naming subtests of the CTOPP-2. Vocabulary was assessed with the Peabody Picture Vocabulary Test, fourth edition, form A (PPVT, Dunn & Dunn, 2007).

2.3. *Materials*

Six categories of images (50 images in each category, for a total of 300 images) were used as stimuli during the EEG portion of the experiment. All images were presented on the same uniform gray background, with dimensions of 480 x 480 pixels. The critical categories were: words, objects, and word/object ambiguous items (“wobjects”). The wobjects were images of words drawn in black with letters shaped to resemble the concept represented by the word (e.g., the word HEART drawn to be shaped like a heart). The wobjects were designed to have a spatial envelope that was object-like but to also include orthographic features, and thus be visually (not semantically) ambiguous. Figure 1 presents examples of the wobjects along with all other item types. Wobjects were created specifically for this research project-- that is, they were not drawn from a database. Word stimuli were first printed in 72 pt san serif font, then each word was stretched to be an exact match in rectangular dimension to a wobject it was matched with. Thus, across items, the spatial extent of the words and wobjects is identical. This is important because the amplitude of the N170 may vary depending on the physical size of the eliciting stimulus (Mercure et al., 2008, De Cesarei & Codspotti, 2006). A second group of 50 words, all in the same 72 pt san serif font, was also included. These were included since during normal reading, the size of text being read does not constantly change from word to word. Thus, there is one category of words that matches the size of the wobjects (“size matched words”), and one category that more closely resembles normal text (“constant size words”)-- when analysis requires comparing words to wobjects, only the size-matched words will be included, in order to avoid potential confounds of size and item type. The three categories containing

images of words (constant size words, size matched words, and wobjects) were matched for length, Coltheart's N, orthographic frequency, bigram frequency, syllable frequency, and number of syllables. These statistics were obtained through MCWord: An Orthographic Wordform Database (Medler & Binder, 2005) and SUBTLEXus (Brysbaert & New, 2009). There were no reliable differences between categories on any of the lexical variables listed above. Objects were black and white photos of common objects all uniformly scaled and cropped to be the same size, and overlain on the same 480 x 480 grey background as all other images. Object stimuli were selected from Google Images.

Two additional categories of stimuli were also included: images of animals, and images of faces. Animals served as the targets for the substantive behavioral task, which was to press a button when an animal was presented. This task was selected because 1) it is developmentally appropriate for even the youngest children in the study and 2) provides evidence that children were attending to the stream of images without contaminating the critical responses (those to the words, objects, and wobjects) with response potentials. Faces were included so that the number of photographic stimuli would be equal to the number of text stimuli (that is, there were 150 photographs: 50 of faces, 50 of objects, and 50 of animals, and 150 vector-text drawings: 50 wobjects, 50 constant size words, and 50 size matched words).

2.4. Procedure

After completing the behavioral reading assessments, children were seated in an electrically shielded, sound attenuated recording booth for EEG acquisition. Children were seated 75 cm away from a 24 inch LCD computer monitor with a 1920 by 1080

resolution operating with a 60 Hz refresh rate and a 1 ms black-to-white response rate. Prior to the beginning of the experiment, each child was shown their EEG record in order to demonstrate what blinks and muscle movement look like-- this demonstration tends to help children better understand the importance of sitting still and following the blinking rules (described below). After this demonstration, each child was guided through an explanation of the experiment that detailed the instructions for responding as well as when blinks were acceptable. More specifically, the explanation instructed children to press a green button on a gamepad with their right hand whenever they saw a picture of a non-human animal, and informed them that they did not have to respond to any other images. Following the explanation, the 300 images were presented in a different, random order for each participant. Each image was only presented once, for a total of 300 experimental trials per participant. The 300 trials were broken down into three blocks of 100 trials, and children were given a break between each block. Children were allowed to determine the duration of their breaks, and were allowed snacks or parental visits during the breaks as desired. The total duration of the experiment was approximately 2 hours.

During EEG recording, the progression of trials was as follows. Continuously throughout the entire experiment, a 480x480 grey box was present in the center of the screen, on top of a black background. Each trial began with a black fixation cross presented in the center of the grey box. The presentation duration of the black fixation cross was jittered around a mean of 500ms. The black fixation cross was followed by a stimulus image on each trial. The images were presented centered in the grey box for 184 ms. 184 ms was chosen for two reasons. First, 184 ms is slightly less than 200 ms

(the approximate upper bound on the time needed to program and execute an eye movement, Rayner & Pollatsek, 1981). Limiting the stimulus duration in this manner means that there will be few, if any, eye movements made to contaminate the EEG record while the stimuli are on the screen. Secondly, 184 is an integer multiple of 16.66666 ms; the frame rate of the 60 Hz monitor. Selecting an integer multiple of the monitor's frame rate for stimulus duration reduces the likelihood of imprecise stimulus timing due to the monitor's physical limitations. A second black fixation cross followed the presentation of each stimulus. This second black fixation cross remained on the screen for 800 ms. Children were still able to enter behavioral responses during this second presentation of the fixation cross, however, trials were not self-paced-- that is, the experiment continued to the next trial at the end of the 800 ms whether or not the participant registered a response. Following the response interval, a white fixation cross appeared on the screen for 1500 ms. Children were instructed that they should attempt to blink and move their eyes only when the white cross was on the screen. Following the blink fixation, the next trial began automatically, beginning once again with a black fixation cross jittered around a mean of 500 ms.

2.5. EEG recording

EEG was recorded from 26 EasyCap Fast 'n Active Ag/AgCl active amplification electrodes embedded in a geodesically arranged elastic EasyCap. Online, EEG electrodes were referenced to the left mastoid, and then later re-referenced offline using an average reference¹. The electrooculogram (EOG) was recorded from two electrodes

¹ All analyses were also conducted with an averaged mastoid reference. The qualitative pattern of results is identical across referencing schemes.

placed on the outer canthi of the left and right eyes (horizontal EOG), as well as one electrode placed on the suborbital ridge of the left eye (vertical EOG). The electrodes placed near the outer canthi were used to monitor horizontal eye movements while the electrode placed on the suborbital ridge was used to monitor blinks. Online, the vertical and horizontal EOG were referenced to the left mastoid. Offline, the vertical EOG was re-referenced to the average of the left and right mastoid, and the horizontal EOG was re-referenced as a bipolar channel. EEG and EOG were recorded using a high pass filter with a 10s time constant and a 6 dB/octave falloff as well as a low-pass filter of 250 Hz with 30 dB/octave falloff. The sampling rate for EEG and EOG was 500 Hz with an A/D resolution of 16 bits. Interelectrode impedances were kept below 50k Ω (Laszlo, Ruiz-Blondet, Khalifian, Chu & Jin, 2014).

Prior to EEG averaging, each participant's data was individually subjected to offline artifact rejection and correction. Correction took place first, via ICA decomposition: data were high-pass filtered (0.05 Hz) prior to ICA decomposition. ICA components demonstrating the scalp topography of blinks were removed. After ICA correction, remaining artifacts not captured well by ICA (e.g., blocking, drift, EMG, and horizontal eye movements) were removed via a thresholding procedure, where the threshold for artifact rejection was individualized for each participant. Artifact correction and rejection, and all other post-processing was performed in EEGLab (Delorme & Makeig, 2004). In order to be included for data analysis, a participant's dataset needed to retain an average of at least 50% of trials (25 / 50) from each of the six categories. The average number of trials retained per category across all children included in data analysis was 40.07/50, and this number was not significantly different across stimulus

types (average number of trials retained per category: words = 40.7/50, size-matched words = 39.65, wobjects = 39.75, objects = 40.3). Following artifact rejection, EEG was filtered for measurement with a band-pass of 0.2-20 Hz. The artifact rejected and filtered EEG was then averaged. ERPs were formed for each of the 6 item types. Each ERP included a 100 ms pre-stimulus baseline as well as a 998 ms post-stimulus record.

2.6. Statistical methods

The linear mixed-effect regression (LMER) framework was used for ERP data analysis, as it has been shown to be well suited for psycholinguistic experiments (e.g., Baayen, 2008). In this particular instance, it is likely that not all items are equally effective (that is, not all of the wobjects are equally ambiguous), and it is also likely, by hypothesis, that individuals will differ in their responses to the critical stimuli. Unlike traditional, factorial means of data analysis, including F1/F2 analysis, LMER does not require that observations be averaged either over subjects or over items, meaning that inter-subject and inter-item variability are not lost in analysis. This characteristic of the LMER approach makes it especially appropriate for use here. We will adopt a minimal (“parsimonious”) random effects structure (see Bates, Kliegl, Vasishth, & Baayen, 2015), as model comparison work conducted in the domain of ERP data analysis has suggested that 1) maximal random effects structures are likely to result in models that are either over-fit or fail to converge in this domain and 2) there is very little impact of fully specifying the random effects structure on model parameter estimates in analyzing data of this type (Stites & Laszlo, 2015).

One difficulty in analyzing developmental ERP data can be selecting time windows for component analysis. Window selection is already difficult in adults (for

review, see Luck, 2014), and in children this can be exacerbated by increased variability in component timing. This difficulty is especially poignant in designs like that employed here, where individual differences are key to the experimental questions. Because *a priori* window selection can be difficult, here we will adopt a data-driven approach to identifying component windows of interest. In particular, we will utilize an extension of the LMER framework based on Growth Curve Analysis (GCA, see Mirman, Dixon, & Magnuson, 2008; see also Stites & Laszlo, In Revision). In this approach, ERP mean amplitude measurements are taken every 10 ms, instead of in only one, larger, component window, and then time is included as a factor in the LMER model (e.g., Stites & Laszlo, 2015; Stites & Laszlo, In Revision). The factor of time can then be allowed to interact with the dependent measures of interest, in order to determine, in a data-driven manner, when those measures have an impact on the ERP. For example, here, we will allow our phonological awareness and vocabulary measures to interact with the time factor. This will tell us when PA and vocabulary impact the ERP, with 10 ms temporal resolution, without having to select a time window for analysis *a priori*. In the analyses presented here, ERP amplitude was measured across 25 consecutive 10 ms time windows from 0 - 250 ms post stimulus onset (e.g., 1-10 ms, 11-20 ms, etc; baselined to -100 - 0 ms). In order to deal conservatively with the fact that the GCA looks for effects in 25 time windows, we adopted a critical t-value of $t > |3.20|$, which corresponds to a model-wise alpha of .002 (.05 / 25). We additionally employed a clustering criterion, such that in order to be considered reliable, a parameter estimate had to exceed the critical t-value in at least two consecutive time bins (see Laszlo & Federmeier, 2014; Stites & Laszlo, In Revision). This approach is more conservative

than other methods for controlling the false positive rate in time series analysis (e.g., the False Discovery Rate [FDR] approach; Maris & Oostenveld, 2007). All statistical analyses were performed in R (R Core Team, 2015), and LMER was implemented via the `lme4` package (Bates, Maechler, Bolker, Walker, 2015).

3. Results

3.1. *Behavioral Results: Phonological and Vocabulary Assessments*

The average score on the standardized vocabulary measure (PPVT) was 114.65 (standard deviation, $\sigma = 13.9$). The average score for the standardized measure of phonological ability (CTOPP-2) was 101.3 (standard deviation $\sigma = 16.26$). These mean standardized scores fall within the “average” range of standardized scores for both assessments (CTOPP-2, Wagner, Torgesen, Rashotte, & Pearson, 2013; PPVT, Dunn & Dunn, 2007). These results indicate that the behavioral measures were at an appropriate level of difficulty, as participants were near neither ceiling nor floor on the measures provided, and, on average, performed at an average level with respect to the normed sample. **Figure 2 displays the distribution of CTOPP and PPVT scores.**

3.2. *Behavioral Results: Animal Detection Task*

During EEG recording, participants were asked to press a button on a gamepad with their right hand when a picture of an animal (non-human) appeared on the screen. Participants averaged 46.15/50 (92.2%, $\sigma = 5.35$) hits (a button press to a picture of an animal). The average number of false alarms (a button press to an image other than an animal) was 9.1/250 (3.6%, $\sigma = 5.5$). These results indicate that participants were actively attending to the presented stream of visual stimuli.

3.3. ERP Results

Figure 3 displays the grand averaged response, across all participants, to size matched words, wobjects, and objects across the entire scalp. It is evident in the figure that N170s are maximal over the left and right lateral occipital sites (boxed). This is consistent both with the wider literature, which has demonstrated that N170 effects tend to be maximal over lateral occipital channels (see Rossion & Jacques, 2012), and with our own work with these items and this task in adults (Laszlo & Sacchi, 2015). For this reason, the remainder of the analyses, which focus on N170 effects, will be restricted to the right and left lateral occipital electrodes (a topographic analyses conducted over the 160-190 ms N170 window identified by the GCA, below, confirmed that N170 effects were in fact largest over the left and right lateral occipital electrodes).

ERP data were first trimmed for LMER. Data were trimmed per subject, such that any observation that was more than 2.5 standard deviations larger or smaller than a subject's mean amplitude was removed. This is similar to applying an amplitude threshold for artifact rejection but has the advantage that it takes inter-subject variability into account, by rejecting only trials that are excessively large or small for each individual subject. Trimming resulted in the removal of 1.82% of size-matched word observations, 1.89% of wobject observations, and 1.68% of object observations.

We first sought to demonstrate that we replicated typical N170 effects pertaining to item type and lateralization in this dataset. In particular, we sought to replicate prior findings demonstrating that objects tend to elicit more bilateral or right-lateralized N170s, when compared with text, which tends to elicit more left-lateralized N170s (e.g., Rossion et al., 2003). We therefore constructed a model where the response variable

was N170 mean amplitude measured between 160-190 ms post stimulus onset, as measured from left and right lateral occipital channels in response to words and objects. We will refer to this as the *replication model*. The 160-190 ms window was selected on the basis of the GCA analysis, conducted below. In the replication model, subject and item were included as random factors (random intercepts only). Fixed factors were age, channel, and item type (word and object). Item type was allowed to interact with channel-- this is what enables the analysis of lateralization effects. The model revealed a significant interaction between item type and channel ($F = 10.37$, $p < .001$). Figure 4 displays the corresponding ERP data: grand averaged ERPs elicited in response to words and objects over the left and right lateral occipital channels. Figure 4 reveals that the interaction between item type and channel seems to be driven by the fact that the overall response to words was more left lateralized, while the overall response to objects was more right lateralized. This is consistent with the existing literature (e.g., Rossion et al., 2003; Maurer, Brandeis, & McCandliss, 2005).

Having successfully replicated relevant N170 lateralization results, we next move on to novel questions for analysis. The primary question under investigation here is whether or not phonological awareness impacts the lateralization of the N170 in response to words. In order to address this question, we first constructed a model where the outcome variable was a difference score computed by subtracting the mean amplitude of the N170 for each word over the right lateral occipital channel from the mean amplitude of the N170 for that same word over the left lateral occipital channel. That is, the outcome variable is the left - right N170 mean difference for each word-- essentially the magnitude of left lateralization for each word. This model included fixed

factors of time, CTOPP score, PPVT score, and age. PPVT was included in the model in order to determine whether phonological awareness specifically, or verbal ability more generally, is related to left-lateralization of the N170. PPVT and CTOPP were allowed to interact with time, in order to determine when during the 0-250 ms post-stimulus onset time window these skills predicted ERP lateralization. Model random factors were item and subject (random intercepts only). We will refer to this model as the *words model*.

In the words model, CTOPP significantly predicted ERP lateralization between 160 and 190 ms post-stimulus onset-- a window corresponding to the canonical timing of the N170. Table 1.a provides t-values and their corresponding p estimates for the time by CTOPP interaction for each significant time bin in the words model. Neither PPVT nor age significantly predicted ERP amplitude in any time window. This result suggests that N170 lateralization is related to individual phonological ability, but not individual language ability or development more generally. Figure 5 displays the CTOPP * time interaction t-scores. Figure 6 displays PPVT * time interaction t-scores, for comparison. The associated ERP data are presented in Figures 7 and 8. Figure 7 displays ERPs elicited in response to words in individuals with the highest and lowest CTOPP, alongside topographic maps of the word N170 effect in these groups. Figure 8 displays ERPs elicited in response to words in individuals with the highest and lowest PPVT, alongside topographic maps of the word N170 in these groups. In both figures 7 and 8, participants were split into two equal groups of 10, with 10 participants in the high performing group and 10 participants in the low performing group. Note that while we present two groups for ERP visualization purposes, no grouping factors were used in

the LMER analyses. Table 2 provides summary (mean and standard deviation) statistics.

As Figure 7 demonstrates, the effect of CTOPP on N170 lateralization observed in the model is driven by the fact that word responses tend to be more left lateralized in participants with higher CTOPP scores. This shift in the distribution of the N170 can also be seen in the accompanying topographic map. As the relationship between phonological awareness and N170 lateralization was of critical interest here, we further explored this effect by computing an N170 lateralization score individually for each participant. This was computed as N170 mean amplitude between 160 and 190 ms over the left lateral occipital channel minus N170 mean amplitude between 160 and 190 ms over the right lateral occipital channel. Out of the 20 participants, the majority (12) displayed mean left-lateralized N170s. The remaining 8 instead mean right-lateralized N170s. Interestingly, 6 of the 8 children who displayed right-lateralized N170s to words were from the bottom half of CTOPP performers. This result indicates that while, in aggregate, our participants displayed the canonical N170 left-lateralization for text, individual children with less phonological awareness tended to elicit more right-lateralized N170s for text.

Having now observed that phonological awareness does significantly predict the lateralization of the N170 in response to words, a secondary question for analysis was whether the N170 tends to be more left lateralized in response to visual stimuli in general in individuals with greater phonological awareness, or whether this effect is restricted to words or items that are word like. To address this question, we next constructed two more models, identical to the previous one, except that the outcome

measures were now (1) laterality of the N170 response to wobjects (*wobjects model*) and (2) laterality of the N170 response to objects (*objects model*).

In the wobjects model, CTOPP scores were not predictive of ERP lateralization in any time window. Wobject model CTOPP * time t-scores are available in Figure 5. PPVT scores were also not a significant predictor of N170 lateralization in the established N170 time window (160-190 ms). However, the time by PPVT interaction was significant during the 90 - 140 ms window, as pictured in Figure 6. Table 1.b provides t-values and their corresponding p estimates for the time by PPVT interaction for each significant time bin. We return to this result in the Discussion. Age was not a significant predictor of ERP lateralization in any time window.

In the objects model, CTOPP scores were not predictive of ERP lateralization in any time window (see Figure 5). Age was also not predictive of ERP lateralization in any time window. However, PPVT did significantly predict ERP lateralization from 110 - 250 ms post stimulus onset. This is visible in Figure 6. Table 1.c provides t-values and their corresponding p estimates for the time by PPVT interaction for each significant time bin.

If the words model, wobjects model, and objects model are compared, a pattern emerges. Specifically, CTOPP score becomes more predictive of N170 amplitude as items become more word-like, while PPVT score becomes more predictive of N170 amplitude as items become more object-like. This is visible in Figures 5 and 6. We will return to this result in the discussion.

A final question for analysis was whether or not better readers display more differentiation of words, wobjects, and objects, as was observed in adults (Laszlo &

Sacchi, 2015). To address this question, we constructed a model where N170 mean lateralization (measured between 160 to 190 ms post-stimulus onset as the difference of the left and right lateral occipital amplitudes) in response to all 3 critical item types (size-matched words, wobjects, and objects) was the outcome variable. Fixed predictors were item type, PPVT score, CTOPP score, and age; item type was allowed to interact with PPVT and CTOPP scores. These interactions allow us to examine whether item type effects are impacted by **phonological awareness and vocabulary level**. Item and subject were included as random factors (random intercepts only). This model revealed significant interactions of both PPVT and CTOPP with item type (for PPVT, $F = 37.927$, $p < .001$; for CTOPP, $F = 8.673$, $p < .001$). In Figure 7, it is evident that the significant interaction of item type with CTOPP is driven by the fact that individuals with higher CTOPP scores did, in fact, display greater differentiation of these item types than did individuals with lower CTOPP scores. Figure 8 shows a similar pattern of results for the PPVT interaction-- those participants with lower PPVT scores show less differentiation between item types, particularly in terms of differentiation between words and wobjects.

4. Discussion

We set out to investigate an untested prediction of the Phonological Mapping Hypothesis-- namely, that the extent to which text processing becomes left-lateralized during reading development should be related to phonological ability. This prediction is rooted in core components of the Phonological Mapping Hypothesis, which posits, essentially, that the brain's response to reading becomes more left-lateralized with experience because left hemisphere auditory language regions become increasingly

called upon to perform phonological mapping-- the linking of orthography with phonology (see Maurer & McCandliss, 2007). This being the case, the greater an individual's phonological awareness, the greater should be the left-lateralization of their processing of text. We addressed this prediction directly here, by asking whether the extent of N170 left-lateralization in response to words in individuals is predicted by their phonological awareness. The left-lateralized N170 elicited by readers in response to word forms is thought to reflect orthographic decoding, as evidenced by the fact that, for example, individuals who learn a new type of print by sub-lexical means elicit left-lateralized N170s in response to the novel print after training, while individuals who learn the same print via whole-word methods do not (Yoncheva et al., 2010). Thus, under the Phonological Mapping Hypothesis, the greater extent to which orthography is being mapped to phonology (reflecting greater phonological awareness), the greater left-lateralization that should be observed on the N170.

In addition to asking the basic-level question of whether N170 lateralization in response to words is, as predicted, impacted by phonological awareness, we additionally asked two further questions, regarding the specificity of potential N170 lateralization effects. First, we asked whether the N170 is more left lateralized during print processing in better readers generally, or whether increased N170 left-lateralization is specifically tied to phonological awareness (and not vocabulary, another measure of verbal ability, or, even more generally, age and consequent cognitive development). Second, we asked whether the N170 is more left lateralized for readers with more phonological ability generally, irrespective of stimulus type, or whether the relationship between phonological awareness and N170 lateralization is restricted to

word-like stimuli. In sum, we wanted to learn (1) whether the N170 in response to words is more left-lateralized in individuals with more phonological awareness, (2) whether the N170 in response to words is more left-lateralized in better readers generally, or specifically in readers with better phonological awareness (and not, for example, readers with larger vocabularies or just older readers), and (3) whether the N170 is more left-lateralized generally in individuals with more phonological awareness, or only displays this pattern to the extent that the eliciting stimulus is word-like.

Before addressing these questions, we first verified that we had replicated canonical N170 lateralization results. Indeed, we observed here, as is typical, that N170s were in general more left lateralized to words than to objects. This pattern is visible in Figure 4. This replication provides additional confidence in the novel results we report next.

As is displayed in Figure 7, the N170 was more left lateralized in response to words in individuals with greater phonological awareness. This result straightforwardly conforms to the Phonological Mapping Hypothesis. Furthermore, this pattern is specific to phonological awareness: that is, when vocabulary, age, and phonological awareness are all included in the same model predicting N170 lateralization, vocabulary and age are not reliable predictors of N170 lateralization. This means that it is not the case that better or more advanced readers generally display more left-lateralized N170s in response to text, but that phonological awareness, specifically, is driving the lateralization of the N170. Finally, the relationship between phonological awareness and N170 lateralization was demonstrated to be a function of how word-like the eliciting stimulus is. N170s were strongly more left-lateralized in individuals with greater

phonological awareness in response to words, marginally more left-lateralized in individuals with greater phonological awareness in response to word/object ambiguous items (“wobjects”) and not more left lateralized in individuals with greater phonological awareness in response to objects. This pattern is visible in Figure 5. What this pattern implies is that increasing phonological awareness does not increase the left-lateralization of the N170 generally, but only to the extent that the eliciting stimulus is word-like. Overall, then, results are strongly consistent with the Phonological Mapping Hypothesis.

Two potentially unexpected results did emerge in the models. First, N170 lateralization in response to objects was predicted by our measure of vocabulary: the PPVT. Figure 6 displays t - values over time for the PPVT by time interaction, indicating that PPVT significantly predicted the N170 difference score in a wide range of time (110 - 250 ms post stimulus onset) that included the N170 window. This result is highly sensible when the exact nature of the PPVT is considered-- on each trial, participants are required to select one image (out of a set of four) that best corresponds with a target word for that trial (For example, the experimenter says “car”, and the participant has to point to an image of a car that is presented in an array with a fork, a table, and a doll). Though the PPVT is widely regarded as a good measure of receptive vocabulary (See D’Amato, Gray, & Dean, 1988; Altepeter, 1989; Dunn & Dunn, 2015), it is also, fundamentally, an object recognition task. It thus makes sense that PPVT score would relate to the ERP response to objects. As is visible in Figure 6, the relationship between PPVT and ERP lateralization became weaker as items became less object-like. Specifically, PPVT reliably predicted N170 lateralization to objects, more weakly

predicted N170 lateralization to wobjects, and even more weakly predicted N170 lateralization to words.

The second unexpected result is that PPVT predicted ERP lateralization in an earlier, pre N170 time window (110 - 160 ms, likely the P1 window), for the wobjects only. It is not clear why this was observed. As the current study was designed to investigate effects of phonological awareness on the N170, not effects of vocabulary on the P1, we hesitate to interpret this effect beyond noting it for future investigation. To explore the P1 effect, and ensure that our N170 results were not influenced by P1 item type (word, wobject, object) effects, we built a model which focused solely on the P1 time window. This model examined effects of item type on ERP mean amplitude in the 110-160 ms window over the left and right middle occipital electrode sites (the sites used in the N170 analyses). This model revealed no significant effect of item type, as well as no significant interaction between item type and channel. This suggests that item type alone, at least, did not significantly predict the mean amplitude of the P1.

Comparison with the Adult Wobject N170 (Laszlo & Sacchi, 2015)

In our work with these items and this task in adults (Laszlo & Sacchi, 2015), we observed a pattern wherein more experienced readers displayed greater differentiation on the N170 between words, wobjects, and objects than less experienced readers. One question raised by that result, however, was whether the de-differentiation observed in the less experienced readers was a *result of* reading less or a *cause of* reading less. That is, while it certainly is reasonable to imagine that the visual system becomes more tuned for word recognition with more experience, it is also at least remotely plausible that individuals who have a relatively difficult time distinguishing letter strings from other

types of visual stimulation may enjoy reading less or seek it out less. One question we hoped to address here, then, in addition to those pertaining to phonological mapping, was whether it takes a lifetime of experience for cortical de-differentiation between these item types, or whether a similar pattern can be observed even in relatively young readers. As Figure 7 demonstrates, individuals with poorer phonological awareness here differentiated the word, wobject, and object item types less strongly than did individuals with greater phonological awareness, particularly over the left hemisphere. Similar results were found with vocabulary, where those with scoring lower on the PPVT displaying less differentiation between item types -- particularly in terms of the N170 response to words and wobjects (see Figure 8). This suggests, minimally, that the poor cortical differentiation of words from objects and wobjects in poorer readers we observed in adults is a phenomenon that does not take over a decade of reading experience to build up. The readers included in this sample are, still, relatively mature (mean grade: 5.5), and are thus on average past the point where, in the literacy literature, they would typically be considered to still be “learning to read” (namely, 4th grade; Chall, 1983). A question that we consider interesting, then, is whether N170 de-differentiation of these item types can be observed in poorer readers at an even earlier stage of reading development. We are currently pursuing this question by replicating the experiment conducted here (and in adults; Laszlo & Sacchi, 2015) in a sample of children in grades K-3. If poorer N170 de-differentiation of these item types is observed in even these less developed readers, it might suggest that cortical inability to differentiate words from other stimulus types could be a contributor to, instead of only a result of, poorer reading ability.

5. Conclusion

Overall, results were broadly consistent with the phonological mapping hypothesis: individuals with greater phonological awareness did demonstrate greater left-lateralization of print processing than did individuals with poorer phonological awareness. This relationship was shown, additionally, to be specific to phonological awareness (and not apply to vocabulary or age more generally) and to be obtained only to the extent that eliciting items are word-like (applying less strongly to wobjects and not at all to objects). Adult work suggesting that better or more experienced readers differentiate visual stimuli such as these more strongly, at the level of the N170, were replicated in this developmental sample, in that individuals with poorer phonological awareness and vocabulary skills displayed less differentiation of these item types on the N170 than did individuals with greater phonological awareness and vocabulary skills. This result suggests that the weak cortical differentiation of these item types observed in less experienced adults can, at least, be observed in individuals with substantially less reading experience than that of a college student. Future work is aimed at addressing whether weaker cortical differentiation of words from other visual stimuli can be observed in even younger readers with weaker skills, in order to address whether poor cortical differentiation could potentially be a contributor to, and not only a result of, reduced reading expertise.

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a.

	Most phonological awareness	Least phonological awareness
Size matched words	-1.56 (16.37)	1.29 (13.56)
Wobjects	-2.91 (15.72)	.019 (12.61)
Objects	-2.08 (16.95)	-0.76 (14.01)

b.

	Highest vocabulary	Lowest vocabulary
Size matched words	-.70 (15.93)	-.51 (14.05)
Wobjects	-2.52 (14.77)	-0.27 (13.71)
Objects	-3.12 (15.61)	.37 (15.31)

Table

a.

Time window	160-170	170-180	180-190
CTOPP	-3.21 (.002)	-3.41 (.0006)	-3.48 (.0004)

b.

Time window	90-100	100-110	110-120	120-130	130-140
PPVT	-3.32 (.001)	-3.91 (<.0001)	-4.68 (<.00001)	-4.53 (<.00001)	-3.76 (.0001)

c.

Time window	110-120	120-130	130-140	140-150	150-160
PPVT	-3.22 (.001)	-3.31 (.0009)	-3.62 (.0002)	-4.13 (<.00001)	-4.511 (<.00001)
Time Window	160-170	170-180	180-190	190-200	200-210
PPVT	-4.55 (<.00001)	-4.40(<.00001)	-4.14 (<.00001)	-3.86 (.0001)	-3.74 (.0001)
Time Window	210-220	220-230	230-240	240-250	
PPVT	-3.75 (.0001)	-3.64 (.0002)	-3.45 (.0005)	-3.32 (.0009)	

Table Legends

Table 1.a. t-scores and corresponding p estimates (in parentheses) for significant CTOPP * Time window interactions in the words only model. b. t-scores and corresponding p estimates (in parentheses) for significant PPVT * Time window interactions in the wobjects only model. c. t-scores and corresponding p estimates (in parentheses) for significant PPVT * Time window interactions in the objects only model.

Table 2. a. Means and standard deviations of N170 lateralization scores for each item type (words, wobjects, objects) for high and low CTOPP performers. More negative numbers reflect a more left-lateralized N170 in response to the category of interest. b. Means and standard deviations for N170 lateralization scores for each item type (words, wobjects, objects) for high and low PPVT performers. More negative numbers reflect a more left-lateralized N170 in response to the category of interest.

TOLL

HEART

MAP

SQUARE

Figure 1

Figure

Figure

Figure

Left lateral occipital

Right lateral occipital

Size-matched words

Objects

Figure

Figure

Figure

Figure

a.

Highest vocabulary

Left lateral occipital

Right lateral occipital

Lowest vocabulary

Left lateral occipital

Right lateral occipital

— Size-matched words
 Wobjects
 — Objects

b.

Highest vocabulary

Lowest vocabulary

Size-matched words - objects

Figure captions

Fig. 1. Sample stimuli. Left: sample objects. Middle: Sample size-matched words.

Right: Sample wobjects. All items were presented on the same 480 x 480 pixel gray background.

Fig. 2. Box and whisker plots for PPVT and CTOPP scores.

Fig. 3. Grand averaged ERPs elicited in response to words, objects, and wobjects over all 26 scalp channels for all participants. The left and right lateral occipital channels, the channels used in our N170 analyses, are boxed. Note that in this figure, and all subsequent figures, positive is plotted up, as is typical in the N170 literature. Also note that in this figure, and all subsequent figures, an average reference was used for offline data rereferencing.

Fig. 4. Grand averaged ERPs elicited by words and objects over left and right lateral occipital channels for all participants. The 160-190 ms N170 window is boxed. Across participants, N170s to objects are more right lateralized, while N170s to words are more left-lateralized.

Fig. 5. t - values for the interaction between time and CTOPP in the word, wobject, and object models. The dashed line is placed at $t = |3.20|$, the criterion employed here for significance (corresponds to $\alpha = .002$). t -values more extreme than this critical t -score were considered reliable. CTOPP is a reliable predictor of ERP lateralization from 160-190 ms post-stimulus onset. This window, which we take as the N170 window for

subsequent analyses, is highlighted by a gray box. Note that, in the N170 window, CTOPP becomes more predictive of ERP lateralization as items become more word-like.

Fig. 6. t - values for the interaction between time and PPVT in the word, wobject, and object models. The dashed line is placed at $t = |3.20|$, the criterion employed here for significance (corresponds to $\alpha = .002$). t -values more extreme than this critical t -score were considered reliable. The N170 window is boxed in gray. Note that, within the N170 window, PPVT becomes more predictive of ERP lateralization as items become more object-like.

Fig. 7. a. Grand averaged ERPs elicited by words, objects, and wobjects over left and right lateral occipital channels in readers with most (top) and least (bottom) phonological awareness. The 160-190 ms N170 window is boxed. b. Topographic map of the N170 word effect (words - objects) from 160-190 ms post-stimulus onset. The N170 word effect is more right lateralized in participants with less phonological awareness. Note that, though participants are split in half for visualization, they were not grouped for analysis; rather, CTOPP score was entered as a continuous variable in the multiple regression.

Fig. 8. a. Grand averaged ERPs elicited by words, objects, and wobjects over left and right lateral occipital channels in readers with highest (top) and lowest (bottom) vocabulary scores. The 160-190 ms N170 window is boxed. b. Topographic map of the N170 word effect (words - objects) from 160-190 ms post-stimulus onset. Once again, the N170 word effect is more right-lateralized in individuals with lower vocabulary

scores. Note that, though participants are split in half for visualization, they were not grouped for analysis; rather, PPVT score was entered as a continuous variable in the multiple regression.