The Directionality of the Relationship Between Left Hemisphere Specialization for Word Reading and High Spatial Frequency Visual Information

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Abstract

Studies show that emerging left hemisphere lateralization for word reading is correlated with emerging left hemisphere lateralization for high spatial frequency (HSF) information. However, it is currently unclear whether left lateralization is partially caused by a pre-existing left hemisphere bias for high spatial frequency visual information (such as that found in words), or if the left hemisphere tuning for HSF is a consequence of reading experience. This study seeks to determine whether lateralization for HSF information exists *prior* to left lateralization for reading. We use a divided visual field task to examine left hemisphere bias for words and for high spatial frequency Gabor patches in pre-readers, early readers, and adults. If left hemisphere specialization for reading occurs due to pre-existing HSF bias in the left hemisphere, than LH specialization for HSF information will be present before children have word-reading ability, i.e., in the pre-readers. In addition, children who demonstrate greater left than right lateralization for HSF may exhibit better word recognition ability. Adults show the predicted left hemisphere lateralization for HSF information and for words, but in pre-readers, neither of these hemispheric biases is apparent. However, it is the case that in both children and adults, a higher left hemisphere bias for high spatial frequency visual information was correlated with a higher left hemisphere bias for words, indicating an early relationship between these two hemispheric biases.

1. Introduction

It is well established that, in most right-handed individuals, the left hemisphere (LH) is specialized for reading and word recognition. Research to support this claim comes from neuropsychological case studies, electrophysiological recordings, and neuroimaging data. For example, reading impairments result from damage to the left occipito-temporal region, specifically the visual word form area, indicating the leftward lateralization of word reading (Hanleyand Kay, 1997, Warrington and Shallice, 1980) . Also, ERP recordings have shown that in adults, the standard electrophysiological marker for pattern recognition, the N170 for words is significantly left lateralized for words as compared to other stimuli, such as faces and symbol strings (Mercure, Dick, Halit, Kaufman & Johnson, 2008; Rossion, Cottrell, & Tarr, 2003).

The left hemisphere lateralization for word recognition seems to emerge over the course of development as letter identification is acquired. Early behavioral studies (Jablonowska & Budhoska, 1976; Davidoff & Done, 1984) showed an emerging right visual field/LH advantage for letters in a divided visual field task, as children develop the ability to name letters. Consistent with this, the left-lateralized N170 is absent in children who have not yet acquired letter knowledge, and the N170 increases as children develop letter knowledge (Maurer et al., 2005). Cross-sectional developmental fMRI studies have found an increased leftward asymmetry related to increases in age and linguistic skill (Schlagger & McCandliss, 2002; Schlagger & McCandliss, 2007; Turkeltaub et. al, 2003).

The contribution of spatial frequency bias to left hemisphere word lateralization

As is evident, there is considerable support for the claim that the LH is tuned for representations of orthographic stimuli and that this organization emerges and is enhanced over the course of development. The question that remains unanswered is why this left lateralization occurs, and in particular, what drives the LH to become specialized for word recognition. One clear and obvious explanation is that it is the LH dominance for language that biases the tuning for word recognition (Dundas et al., 2013). The question is whether this linguistic bias suffices as a complete explanation for the left lateralization of word processing, or whether there might also be a bias in the visual system that predisposes the LH to word acquisition.

One possible mechanism that may underlie the LH lateralization for word reading is the proposed LH bias for high spatial frequency visual input. Spatial frequency refers to the number of contrasting light/dark (luminance) cycles per unit space (for example, one degree visual angle or one inch). Sudden and frequent changes in a given area of space constitute fine edges, or high spatial frequency. The detection of these sorts of fine edges are necessary for discriminating individual letters so that words can be accurately read. It has been shown that a letter can be identified based on a spatial frequency band from 1.5 to 10 cycles per letter (Majaj, Pelli, Kurshan, & Palomares, 2002). Many studies have provided evidence that the two hemispheres show different biases towards particular spatial frequencies. Behavioral studies (Sergent, 1982; Peyrin, Chauvin, Chokron, & Marendaz, 2003) and case studies of patients with left vs. right hemisphere brain damage (Robertson & Ivry, 1998) have demonstrated an increased sensitivity to high spatial frequencies in the left hemisphere, and an increased sensitivity to low spatial frequencies in the right hemisphere. Kitterle et. al (1990) conducted a divided visual field study, presenting high and low spatial frequency gratings to both the right and left visual fields, and found that participants were faster to identify gratings in the range of 6-9 cycles per degree in the right visual field/LH, and faster to identify gratings in the range of 0.5-2 cycles per degree in the left visual field/right hemisphere (RH). ERP studies (Mercure, Dick, Halit, Kaufman, & Johnson, 2008). Functional imaging studies (Seghier & Price, 2011; Woodhead, Wise, Sereno, & Leech, 2011) have supported these data, showing increased LH activation for images and gratings closer to 7 cycles per degree, and increased RH activation for images and gratings closer to 0.5 cycles per degree. This differential preference for high vs. low spatial frequency visual information is particularly pronounced in the left and right fusiform gyri (Woodhead et. al, 2011) but may be maintained throughout cortex. For example, Fintzi & Mahon (2014) reported that the left orbitofrontal cortex accesses high spatial frequency visual information in its contribution to object recognition, whereas the right OFC's contribution to object recognition is primarily based on the low spatial frequency information.

As the processing of high spatial frequency information is important in word identification, it is not surprising that many studies have found strong associations between left lateralization for word reading and LH bias for high spatial frequencies. Seghier & Price (2011) found significant leftward lateralization in the posterior occipitotemporal region for words and letters with high spatial frequencies, but no leftward lateralization for stimuli consisting of low spatial frequencies. Woodhead et. al (2011) found significant differences in spatial frequency processing between the visual word form area of the LH and the fusiform face area of the right hemisphere, particularly a greater activation of the VWFA to high spatial frequencies. Mercure et. al (2008) found that spatial frequency was associated with increased leftward lateralization of the N170 ERP for word recognition.

To highlight aspects of English word reading that may relate to a leftward lateralization, Hsiao & Cottrell (2009) proposed that, in reading English, the visual system is forced to rely on high spatial frequencies for two specific reasons. One is the fact that many letters are shared in English words-for example, we must discern the middle letter identity in order to correctly separate the words "hot" and "hat". Attention to these individual letters requires processing of high spatial frequency information. Second, the visual system must map words into their constituent letters, a task that also requires processing of high spatial frequency information. To assess this, they implemented a model and showed that tasks requiring processing of high spatial frequency elements caused the model to rely more greatly on LH processing (Hsiao & Cottrell, 2009).

Developmental emergence of letter and word perception: A causal account

As evident from this brief overview, the LH dominance for letter and word perception emerges over the course of development. It is also the case that the hemispheres differ in their sensitivity to high spatial frequencies, and that a LH bias to higher spatial frequencies may be associated with LH hemisphere lateralization for reading. What is missing from the literature is an explanation of causality. All past studies showing a relationship between LH language lateralization and high spatial frequency bias have been correlational. Currently, it is impossible to tell whether a sensitivity of the LH to high spatial frequencies causes the LH to become specialized for word reading, or whether the LH becomes more sensitive to high spatial frequency information over the course of development as a result of the role it plays in word reading. Left lateralization for reading may be an outgrowth of an evolutionarily older specialization of the left hemisphere, at the basic sensory level (Dehaene & Cohen, 2007). Interestingly, Adams and Courage (2002) have found that contrast sensitivity to high spatial frequency information reaches adult levels near the age of 4, long before left lateralization for reading ability is thought to occur. This study did not examine development of this sensitivity specifically in the left hemisphere, but it does provide some evidence for a system of spatial frequency processing which develops fully before any reading system is in place. If this is true, then left hemisphere sensitivity to high spatial frequency information should exist before LH specialization for reading occurs.

The Current Study

To test the theory that LH sensitivity to high spatial frequency information contributes to LH specialization for reading, we will study hemispheric lateralization patterns and spatial frequency sensitivities in pre-readers (age 3), early readers (age 5-6), and adults. Words (or letters for the youngest age group) will be presented to each visual field, with the expectation that, as in previous studies, early readers and adults will show a greater degree of left lateralization for identification of letters/words. To measure sensitivity to high vs. low spatial frequencies, Gabor patches at 1.5 cycles per degree and 6 cycles per degree will be presented briefly to both visual fields. Participants will be instructed to indicate when a target shape is present in either visual field, and sensitivity to the different levels of spatial frequencies will be measured by the subjects' response times. We will also examine whether individuals with higher levels of sensitivity to the high spatial frequency information show greater levels of left-lateralization. If, as Hsiao and Cottrell (2009) predict, high spatial frequency sensitivity facilitates accurate word reading, then we predict that children with higher LH sensitivity to high spatial frequency information will have superior word recognition ability.

If left lateralization for reading occurs due to pre-existing high spatial frequency sensitivity in the left hemisphere, we will expect to see some amount of left hemisphere bias to high spatial frequency information in all subjects, even in children who have not yet acquired reading skill. On the other hand, if left lateralization for reading occurs as a *result* of the left hemisphere's reading abilities, then we would expect pre-readers to show far less LH preference for high spatial frequency information than early readers or adults.

2. Experimental Methods

2.1 Participants

The study was approved by the Carnegie Mellon Institutional Review Board and the administrators of the Carnegie Mellon Children's School.

Pre-readers

Fifteen children, mean age of 4.5 years, were recruited from the Carnegie Mellon Children's School. The study was approved by the administrators of the Children's School. An experimenter visited the children at the school for a total of three sessions, one for the spatial frequency task, one for the letter identification task, and one for an assessment of early reading abilities. Each task took no longer than 20 minutes, as per Children's School regulations. Children with a history of visual, developmental, or neurological disabilities were excluded from the study, as were children whom teachers observed to be left-handed.

Adults

31 adults, all undergraduate students at Carnegie Mellon University, participated in the spatial frequency identification task, and 25 of these 31 adults participated in the word identification task. Each individual came to the lab for a one-hour session, and received $10 or course credit as compensation. All adult participants were right-handed (Edinburgh Handedness Inventory score of 40 or higher), native readers of English, and had no history of visual or neurological problems, and had no history of reading difficulties.

2.2 Stimuli

Gabor patches at 1.5 cycles per degree and 6 cycles per degree were generated using MATLAB software. For the adult participants and early readers, the patches were presented at a contrast level of 0.3, but this level was increased to 0.4 for the youngest children. These parameters were determined based on the results of pilot data, when it was determined that a 0.4 contrast level was necessary in order for the youngest children to achieve an accuracy level above 70%. The Gabor patches were 1.5 inches in height and 1 inch in width, and 130 x 130 pixels. The screen resolution of the laptop on which these patches appeared was 1366 x 768. Four patches in total were shown in each experiment, at both spatial frequency levels and at either a horizontal or vertical orientation. The stimuli appeared against a black background.

Word stimuli were taken from a prior experiment (Dundas et. al, 2012), and consisted of 60 four-letter words in gray Arial 18 point font appearing against a black background. The words were approximately ½ inch in height and 1 inch in width. Pairs of words were constructed so that words would differ by one of their interior letters, in order for a same/different task to be performed.

Letter stimuli used in the pre-reader's task were in gray Arial 18 point font, and appeared against a black background. The letters were approximately ½ inch in height and in width. The thirteen most commonly used letters, according to the Oxford English Dictionary, were use as stimuli in the experiment.

2.3 Experimental Procedure

The experiment was run on a laptop using E-Prime software, version 2.0 (Schneider, Eschman, & Zuccolotto, 2002). Participants sat 15 inches from the screen for both the word and spatial frequency tasks. For adults, a chinrest was used to limit head movements. Participants sat in a room with the lights dimmed, and were instructed to look directly at the center of the computer screen.

The spatial frequency identification task was similar to the paradigm used by Kitterle et. al (1990).They were instructed to press a button, either "H" or "G", when the low spatial frequency image appeared, and to press the opposite button, either "H" or "G", when the high spatial frequency image appeared. Whether participants responded "G" for low and “H” for high or “H” for low and “G” for high was counterbalanced across participants. The HSF and LSF stimuli appeared an equal number of times in both the right and the left visual field in each trial. For early readers and adults, the stimuli appeared in either the left or the right visual field for 20 ms (Fig. 1). For the pre-readers, the stimuli appeared in either visual field for 40 ms, a parameter determined through pilot data, as most of the young children were unable to perform the task at a presentation time of 20 ms. Adults and early readers performed 96 trials (presentations) of the spatial frequency task, took a short break, and performed another 96 trials, for a total of 192 trials. The pre-school children performed the task for as long as they were willing, typically for about 60 trials.

The word and letter tasks consisted of a given word or letter appearing in the center of the screen for 750 ms before disappearing, after which another word or letter appeared to the right or left of the screen for 150 ms. The second word or letter appearing either matched or did not match the word presented in the center. (Fig. 2) Participants were told to press “G” or “H” if the two stimuli were the same or different. Whether “G” or “H” indicated same or different was counterbalanced across the trials. Adults and early readers performed 96 trials of this task, took a short break, and performed another 96 trials, for a total of 192 trials. The pre-school children performed the task for as long as they were willing, typically for about 60 trials. The order in which these tasks were presented was counterbalanced across participants in a particular age group.

Finally, the pre-readers underwent the CORE Phonics Survey, a brief assessment of reading ability and letter knowledge. In this survey, the children were shown a set of 26 uppercase and lowercase letters. The experimenter pointed to each letter, and asked the child whether he/she knew what letter it was. Then, the child was shown the same set of letters, and asked if he/she knew what sound the particular letter made. Finally, the children were shown 7 sets consisting of 10 real words and 5 pseudowords. The experimenter pointed to individual words and asked the child if he/she knew what the word was. Responses were recorded to give an overall score of the child’s early reading abilities, in order to explore whether level of reading ability was correlated with left lateralization for letters and high spatial frequency visual information.

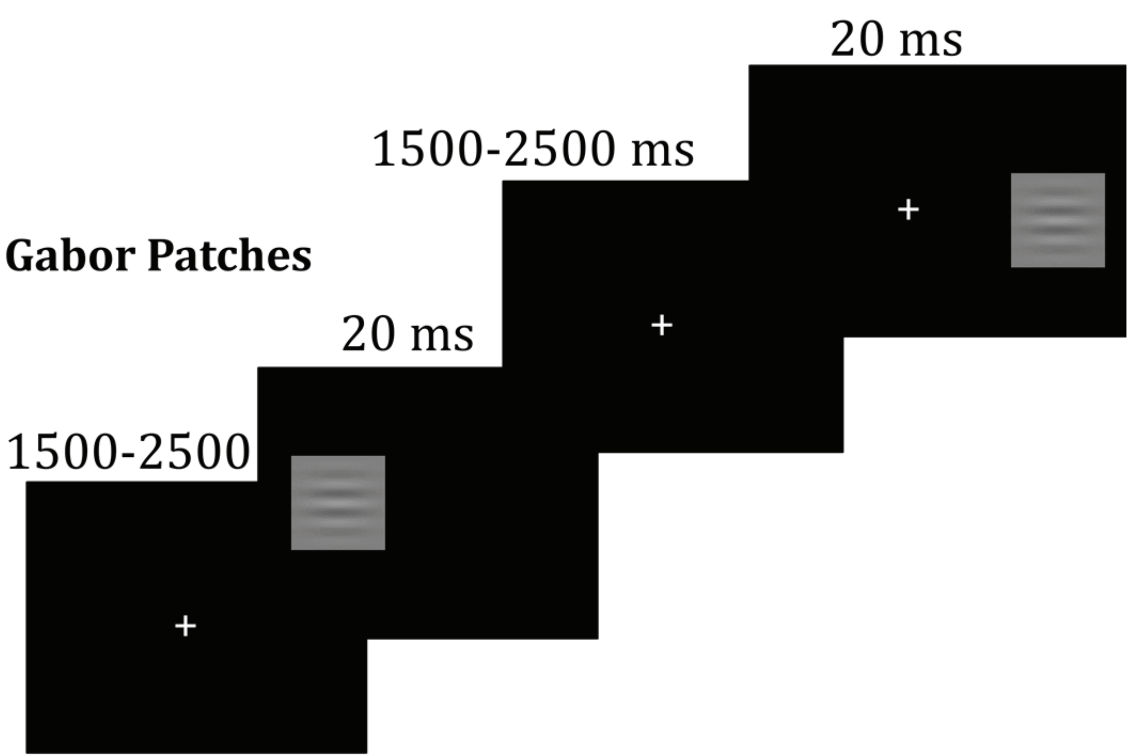


Fig.1. Example of the sequence of stimuli appearing in the SF task.

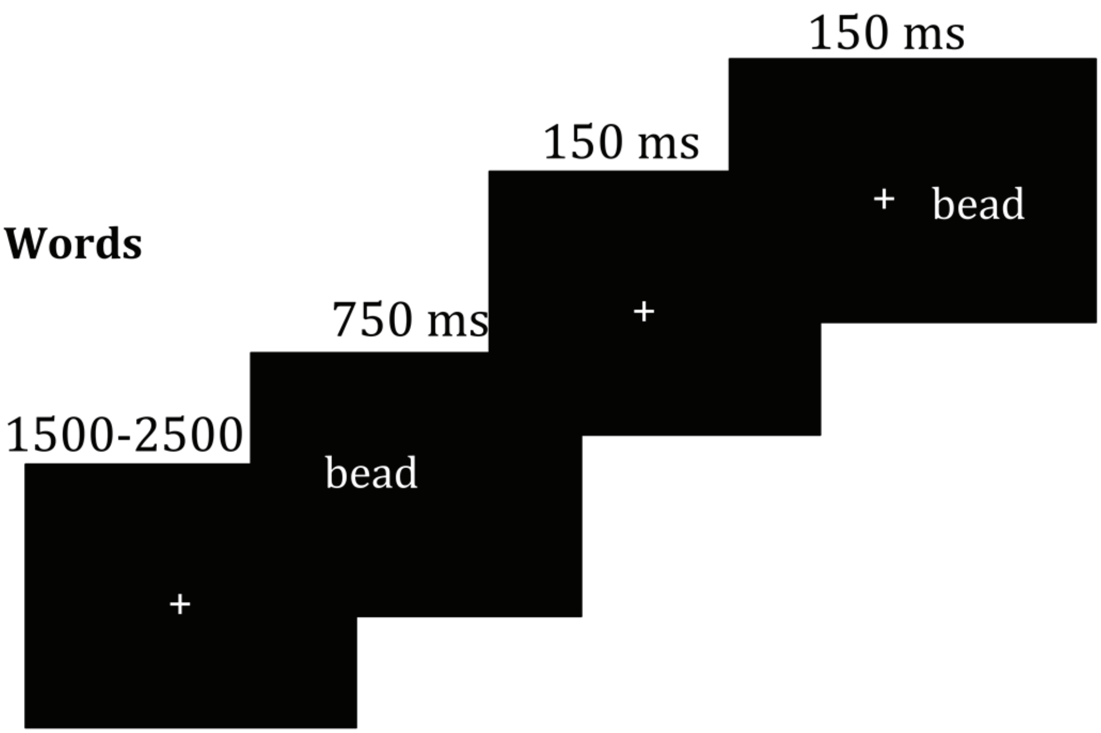


Fig. 2. Example of the sequence of stimuli appearing in the words task.

3. Results

Left lateralization for high spatial frequency Gabor patches in adults
As in the experiments of Kitterle et. al (1990), accuracy for the task was extremely high and over 95 % in most cases. Therefore, it was not possible to conduct any relevant analyses of visual field preference using accuracy as a dependent measure.

We explored reaction time (RT) differences for high vs. low spatial frequency Gabor patches in the right visual field/left hemisphere and the left visual field/right hemisphere using a repeated measures ANOVA Response (G or H for low/high) x Spatial Frequency (High or Low) x Visual Field). The interaction between visual field and spatial frequency was marginally significant ($F(1, 29)= 3.041$, $p = 0.09$), with RT being faster for HSF Gabor patches in the RVF/LH, and faster for LSF Gabor patches in the LVF/RH, the predicted result (Fig. 3).

While the mean difference for low spatial frequency Gabor patches between the left and right visual fields was only about 5 ms (LVF: 583.05 ms, RVF: 577.05 ms), the mean difference in high spatial frequency Gabor patches between the left and right visual fields across the two sessions was about 25 ms (LVF: 580.19 ms, RVF: 555.72 ms). This indicated that the right visual field/left hemisphere bias for high spatial frequency Gabor patches was stronger than the left visual field/right hemisphere bias for low spatial frequency Gabor patches. To confirm the RVF advantage for HSF Gabor patches, we performed a one-way ANOVA on the RT for LVF versus RVF and observed significantly faster RTs in the RVF/LH than in the LVF/RH ($F(1, 29) = 5.819$, $p = 0.022$, Fig. 4). No RT differences in RT were noted for LSF Gabor patches in the two visual fields ($p < 0.05$). The finding of a RVF/LH advantage for high spatial frequency visual information without an LVF/RH advantage for low spatial frequency visual information is consistent with one of the experiments of Kitterle et. al (1990), where the LH advantage for high spatial frequency visual information was more salient and easier to detect than the RH advantage for low spatial frequency visual information. For our purposes, the presence of the RVF/LH advantage for HSF Gabor patches suffices and permits us to examine our hypotheses concerning the relationship of HSF and orthographic processing.

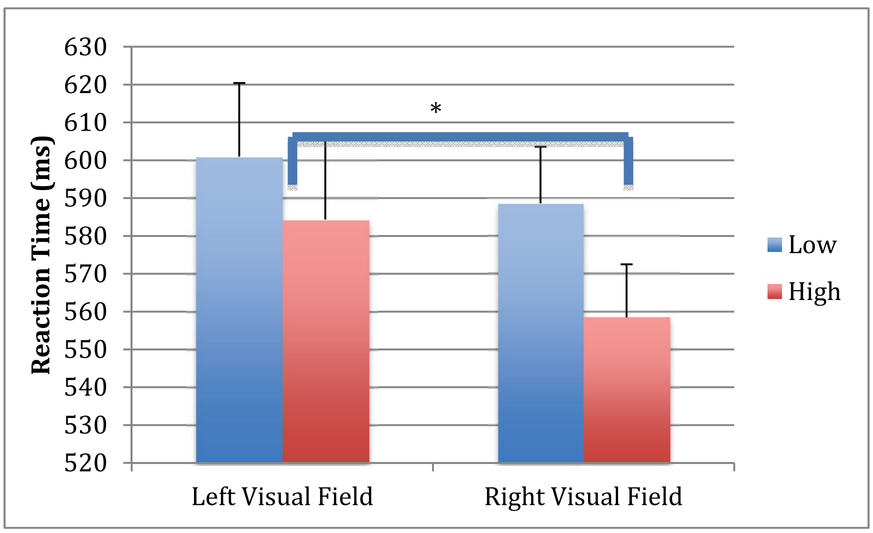
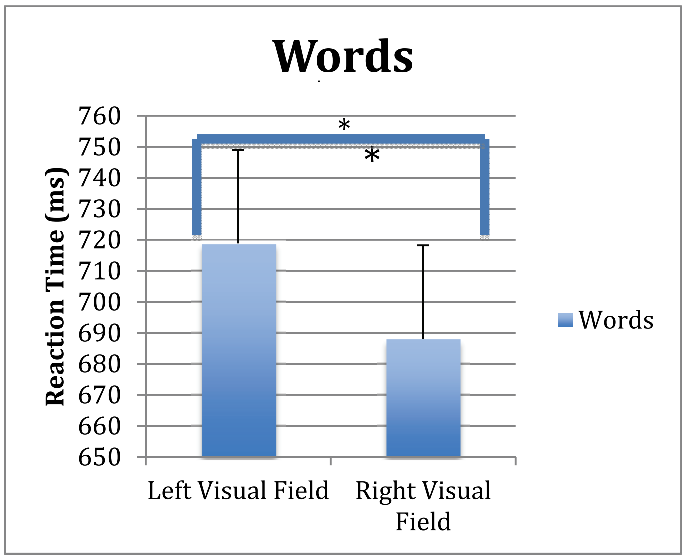


Figure 3. Mean reaction times (RT) for high and low spatial frequency Gabor Patches in the right and left visual fields. RT for high spatial frequency Gabor patches are significantly faster in the right visual field, while RT for low spatial frequency Gabor patches are moderately faster in the left visual field. Significant differences are indicated by (*). Which diffs are sig??

Left lateralization for words in adults

Of the 31 adults, 25 completed the words task and we first examined both RT and accuracy differences in the two visual fields (Fig. 4a). A repeated measures ANOVA (Response(G or H) x Visual Field) found a significant difference between RTs for word stimuli in the right and left visual field, with faster mean RTs in the right visual field ($F(1, 23) = 10.059$, $p = 0.004$). We then examined accuracy and observed a similar finding: a significant effect of visual field, with higher accuracy overall for words appearing in the right visual field ($F(1, 23) = 7.728$, $p = 0.011$).



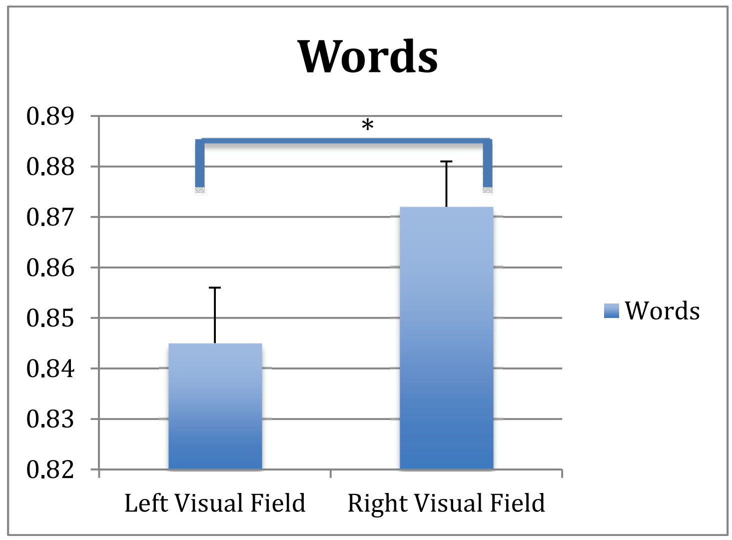


Fig. 4a. Mean RT for words in the left and right visual fields with significantly faster performance in the right visual field/left hemisphere than in the left visual field/right hemisphere. Significant differences are indicated by (*).
Fig. 4b. Mean percent accuracy for words appearing in the left and right visual fields with significantly higher accuracy for words in the right visual field/left hemisphere than for words appearing in the left visual field/right hemisphere. Significant differences are indicated by (*).

Relationship between left lateralization for words and high spatial frequency visual information

To examine whether a relationship was apparent between LH lateralization for words and left lateralization for HSF visual information, we performed a Pearson correlation including the following variables: RT for high and low spatial frequency Gabor patches in either visual field, RT for words appearing in either visual field, accuracy for high and low spatial frequency Gabor patches appearing in either visual field, accuracy for words appearing in the left and right visual fields, the difference in RT for HSF Gabor patches appearing in the left visual field and those appearing in the right visual field, the difference in reaction time for words appearing in the left visual field and those appearing in the right visual field, difference in accuracy for HSF appearing in the left and in the right visual field, difference in accuracy for words appearing in the left and the right visual field, the inverse efficiency measures (Reaction Time/Accuracy) for high and low spatial frequency measures in either visual field, and the inverse efficiency measures (Reaction Time/Accuracy) for words appearing in either visual fields. As predicted, a Pearson correlation between right visual field reaction time for high spatial frequency visual information was positively correlated with right visual field reaction time for words (r = 0.472, p = 0.017, Fig. 5). Based on the ERP experiments of Mercure et. al (2008), which suggested lateralization for words is influenced by spatial frequency, and the neuropsychological studies of Roberts et. al (in press) this is the predicted result. This correlation did not appear when comparing RT for words and high spatial frequency Gabor patches in the first spatial frequency and word session, but did appear in the second session. There was no significant correlation between right visual field accuracy for high spatial frequency visual information and for words, but given the fact that mean accuracy on the spatial frequency task was over 90 %, this may well be due to a ceiling effect.

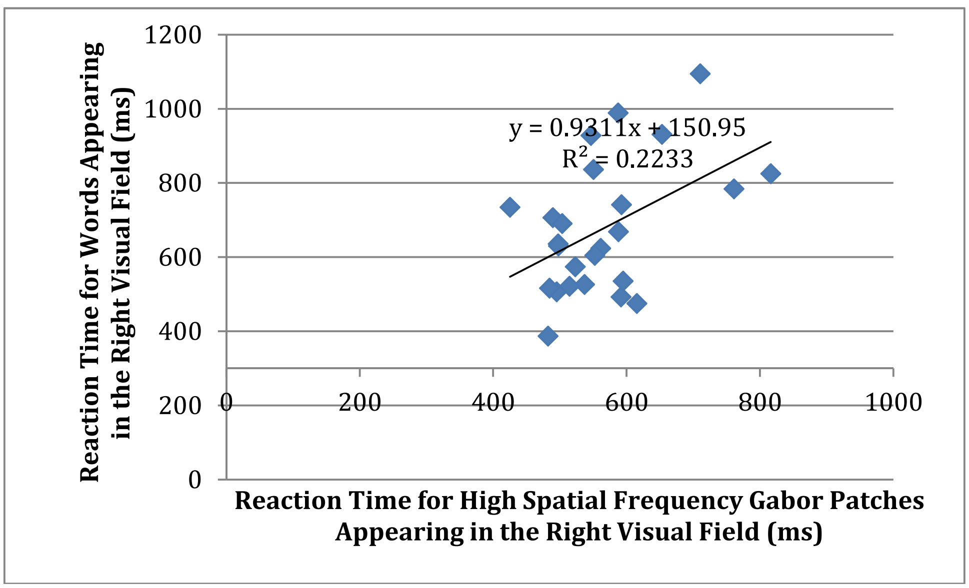


Fig. 5. Reaction time for HSF Gabor patches appearing in the right visual field was positively correlated with reaction time for words appearing in the right visual field. This indicates that individuals who reacted more quickly to HSF visual information appearing in the right visual field also reacted more quickly to words appearing in this visual field.

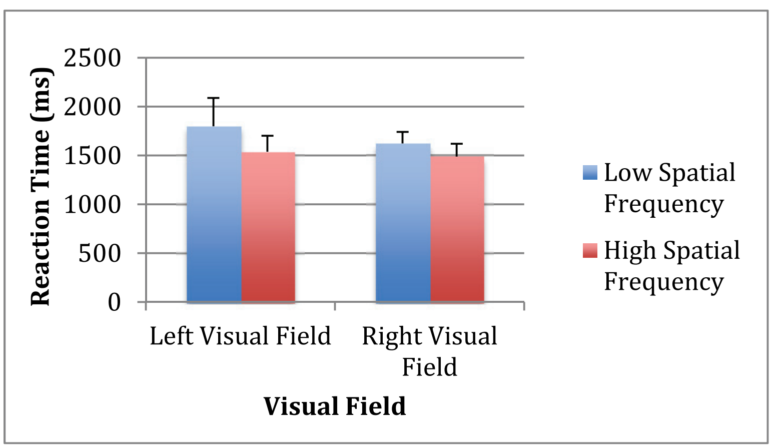
Left lateralization for high spatial frequency Gabor patches in children

15 datasets from children were included in the analysis. 8 of the children responded "G" for the low spatial frequency Gabor patch and "H" for the high spatial frequency Gabor patch, and 7 responded "H" for the low spatial frequency Gabor patch and "G" for the high spatial

frequency Gabor patch. We first examined RT differences in the two visual fields (Fig. 6). A repeated measures ANOVA (Response(G or H for low/high) x Visual Field x Spatial Frequency (High or Low)) yielded no significant differences in RT for high or low spatial frequency Gabor patches in either visual field ($p > 0.1$). We also analyzed differences in accuracy for high vs. low spatial frequency Gabor patches in the right and left visual fields (Fig. 7); a repeated measures ANOVA (Response (G or H for low/high) x Visual Field x Spatial Frequency (High or Low)) found no significant interactions or main effects in accuracy for high or low spatial frequency stimuli in either visual field ($p > 0.1$).

Although no interaction between field x spatial frequency was observed, because we had an a prior prediction about high spatial frequency superiority in the RVF/LH as in the adults above, we examined differences in RT and accuracy for the high spatial frequency Gabor patches in the left and right visual fields. A direct comparison of RT and accuracy for HSF Gabor patches revealed no difference between the left or right visual fields (both $p > 0.1$). The same was true for low spatial frequency Gabor patches in the left and right visual fields in RT or in accuracy (both $p > 0.1$).

Because the pattern of differences between high and low spatial frequency patches in the right and left visual fields were different for reaction time and for accuracy (Fig. 6a, 6b), we explored whether young children experienced a speed/accuracy tradeoff, with inaccurate responses on trials in which their responses were very fast. To adjust for this possible tradeoff, we computed the inverse efficiency scores (RT/Percent Correct) (Townsend & Ashby, 1978, 1983) for each child participant for high and low spatial frequency Gabor patches in each visual field. A repeated measures ANOVA (Visual Field x Response (G or H) x Spatial Frequency) using the inverse efficiency scores for high and low spatial frequency Gabor patches in the left and the right visual fields yielded no significant effects, consistent with the previous analyses.



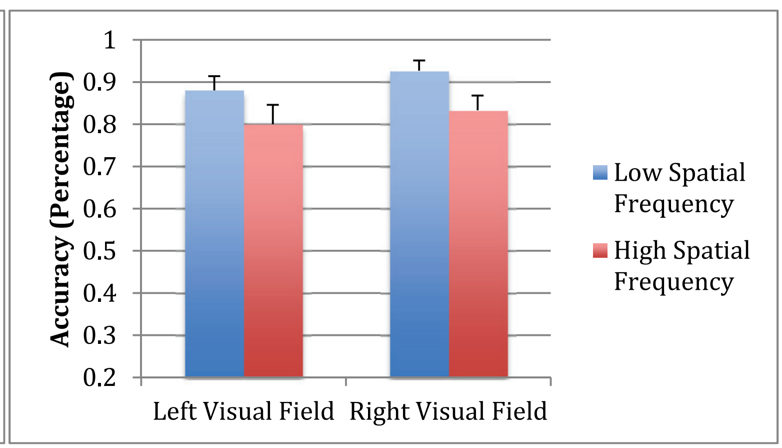


Fig. 5a. Mean reaction times (RT) for high and low spatial frequency Gabor Patches in the right and left visual fields. RT for high and low spatial frequency Gabor patches are not significantly different between the left and right visual fields.
Fig. 5b. Mean percent accuracy for high and low spatial frequency Gabor patches in the right and left visual fields. Accuracy for high and low spatial frequency Gabor patches are not significantly different between the left and right visual fields.

Left lateralization for letters in children

A repeated measures ANOVA (Visual Field x Response (G or H)) yielded no significant difference in reaction time ($p > 0.1$), (Fig. 6a) nor in accuracy for letters in the left vs. right visual field ($p > 0.1$), (Fig. 6b). As with the analysis of high vs. low spatial frequency information in the different visual fields, we computed the inverse efficiency scores for letter stimuli in the left and right visual fields. A repeated measures ANOVA (Visual Field x Response (G or H) x Spatial Frequency) using inverse efficiency scores for words appearing in the left and in the right yielded no significant effects. This result mirrors that of Jablonowska & Budhoska (1976) and Davidoff and Done (1984), in which a RVF advantage for letters was not apparent in children with sparse knowledge of letters. However, it should be noted that in these earlier studies, a left visual field/right hemisphere advantage was often observed in the absence of letter knowledge, whereas in our analysis, no difference at all was found between the two visual fields. It is possible that some small effect does exist, and the sample size was too small for us to detect any visual field differences.

Analysis on top scoring children

We considered the possibility that the absence of hemispheric differences in children might potentially have resulted from a floor effect. It could have been the case that most of the children really showed no reading ability at all, such that reaction times to letters were so slow that a hemispheric advantage could not be detected. We therefore repeated all of the analyses mentioned above on the 8 children with the highest composite reading scores on the CORE Phonics Survey. However, these analyses also yielded no significant differences between the visual fields for high vs. low spatial frequency Gabor patches ($p > 0.1$), and no significant differences between the visual fields for letters ($p > 0.1$). Therefore, we are confident that the results obtained do not reflect a floor effect of very little reading ability.

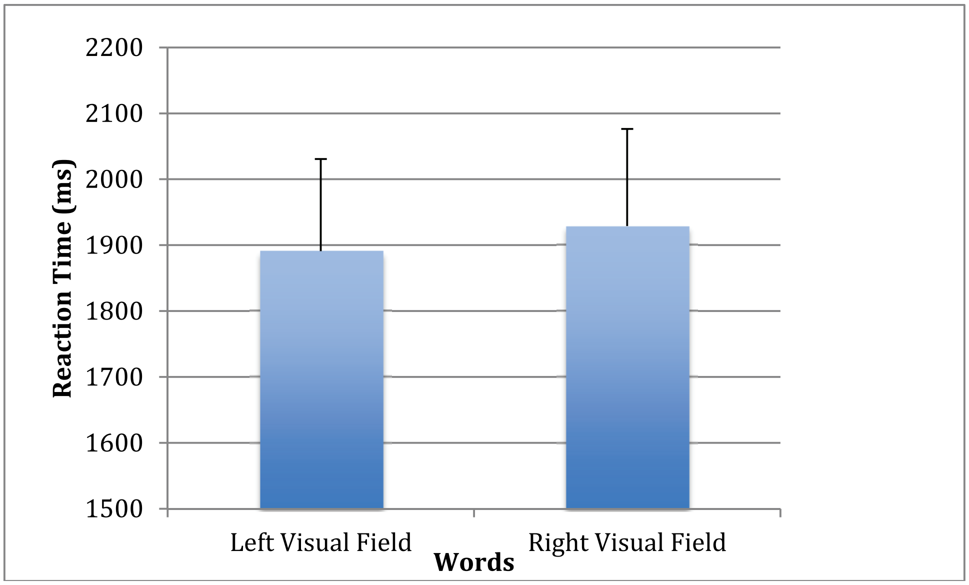


Fig. 6a. Mean reaction times (RT) for letters in the left and right visual fields. No significant difference in RT between the left and right visual field occurred.

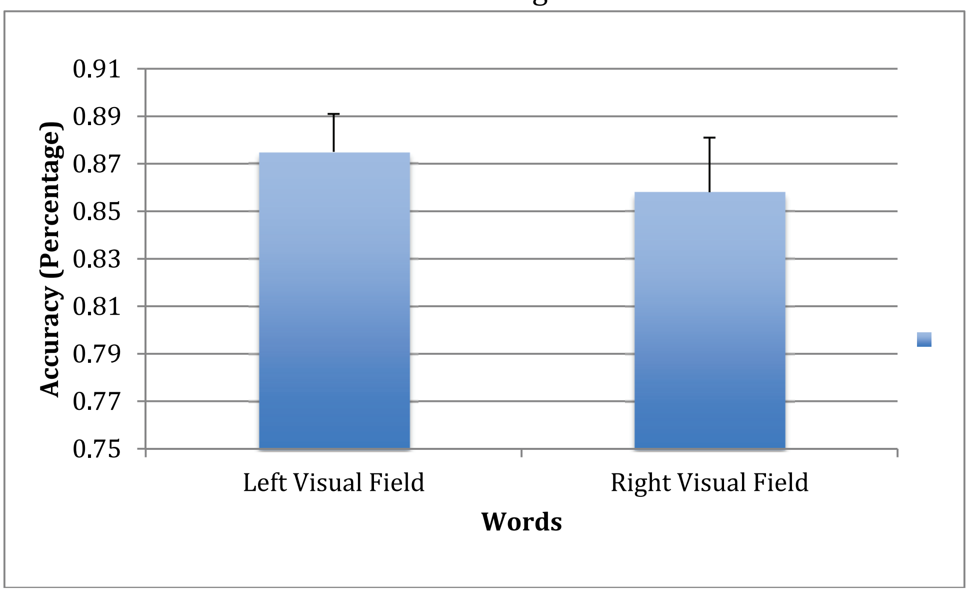
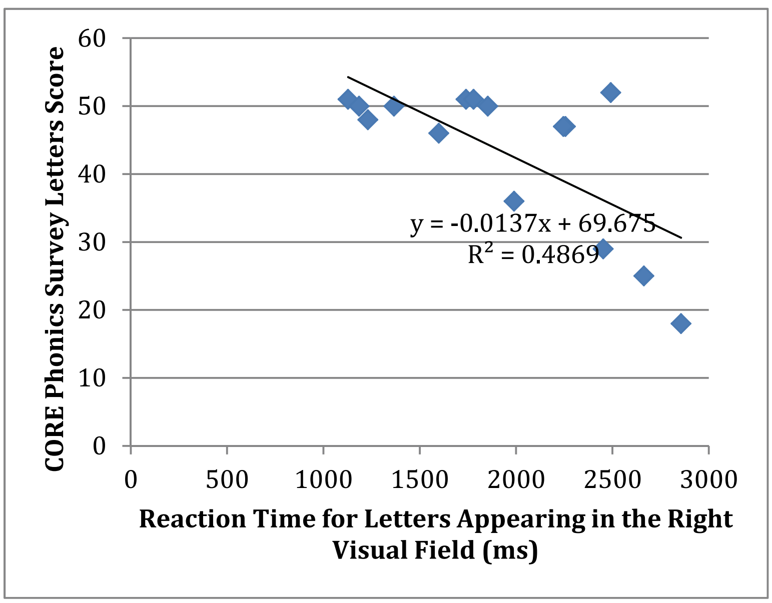


Fig. 6b. Mean percent accuracy for letters in the left and right visual fields. No significant difference in RT between the left and right visual field occurred.

Relationship between left lateralization for letters and reading ability

We conducted Pearson correlations between RT , accuracy and inverse efficiency for letters in the right and left visual fields. For each child, the difference in RT and accuracy for letters between the left visual field and the right visual field and the difference in RT for high and low spatial frequency Gabor patches between each visual field was calculated. Pearson correlations were performed between these differences.

According to our hypothesis, children with a greater RVF advantage for letters (as shown by lower reaction time and higher accuracy) should also have higher scores regarding ability to identify letters, and involving overall reading ability. We found a significant correlation between RT for letter stimuli appearing in the right visual field and letter knowledge as measured by the letter identification scores on the CORE Phonics Survey (r = -0.698, p = 0.004, Fig. 7a). We also found a significant correlation between the inverse efficiency for words in the right visual field and the score for letters on the CORE Phonics Survey (r = -0.607, p = 0.016, Fig. 7b). These results attest to the fact that faster (lower inverse efficiency score) reflect reading ability as measured by the independent, standardized CORE test.



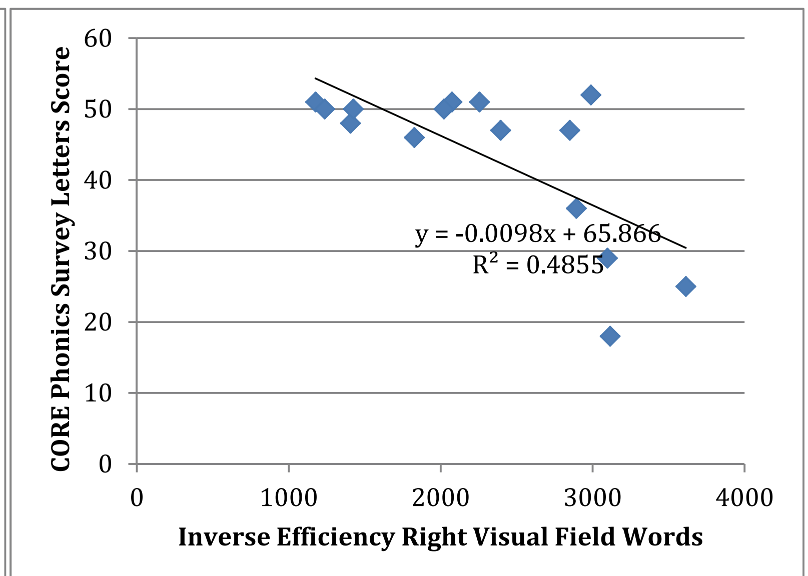


Fig. 7a. Reaction time for letters in the RVF/LH was negatively correlated with letter identification score on the CORE Phonics Survey. This indicates that children with faster letter identification ability in the right visual field also had stronger letter ability.
Fig. 7b. The inverse efficiency measure for letters appearing in the RVF/LH was correlated with higher composite reading scores on the CORE Phonics Survey. This indicates that children with faster reaction times to letters appearing in the right visual field/left hemisphere were also stronger readers.

Relationship between left lateralization for high spatial frequency visual information and reading ability

We conducted Pearson correlations between RT, accuracy and inverse efficiency for high and low spatial frequency Gabor patches in the right and left visual fields. For each child, the difference in reaction time and accuracy for letters between the left visual field and the right visual field and the difference in reaction time for high and low spatial frequency Gabor patches between each visual field was calculated. Pearson correlations were performed between these differences. We did not find significant correlations between RT for high spatial frequency Gabor patches and composite or letter identification score on the CORE Phonics Survey.

Relationship between left lateralization for letters and high spatial frequency visual information

Although we did not find a significant difference between word processing or between high spatial frequency visual information in either visual field for the children, we did find a significant positive correlation between RT for high spatial frequency Gabor patches in the right visual field and RT for letters in the right visual field ($r = 0.600$, $p = 0.018$). This is similar to the correlation found in the adult participants, and indicates that children with faster reaction times to high spatial frequency visual information in the right visual field also show faster RTs for letters in the right visual field. This is consistent with our hypothesis that right visual field/left hemisphere lateralization for high spatial frequency visual information is related to right visual field/left hemisphere lateralization for letters.

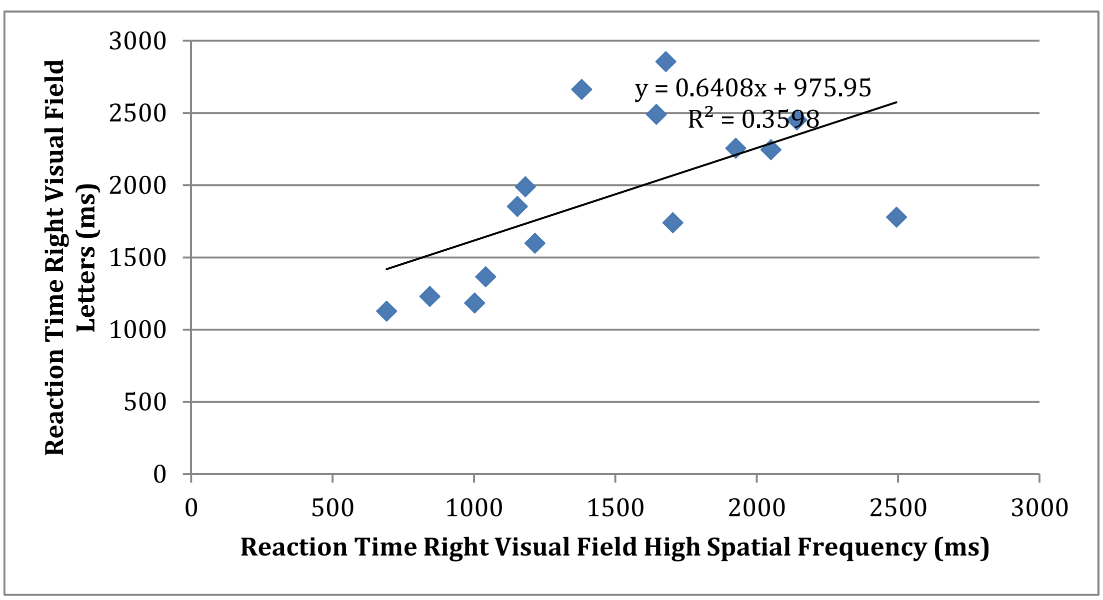


Fig. 8. Consistent with our hypothesis, reaction time for high spatial frequency Gabor patches in the RVF/LH was positively correlated with reaction time for letters appearing in the RVF/LH.

4. Discussion

The goal of this study was to explore whether a left hemisphere bias for high spatial frequency visual information predisposes the left hemisphere (LH) to be specialized for word reading. We sought to examine the level of left hemisphere/right visual field (RVF) bias for high spatial frequency visual information in adults and in pre-reading children. We used a divided visual field task to investigate whether or not the pattern of hemispheric bias as measured by reaction time (RT) and accuracy (ACC) for high spatial frequency Gabor patches and for word/letter stimuli would differ between adults and pre-reading children.

Using our paradigm, adults in this study displayed the typical LH/RVF lateralization for words and high spatial frequency Gabor patches. However, using the same paradigm in pre-reading children, no LH/RVF lateralization appeared for letter stimuli or for high spatial frequency Gabor patches. As expected, reaction times for high spatial frequency Gabor patches in the RVF/LH were correlated with reaction times for word stimuli in the RVF/LH. Interestingly, this correlation was also apparent in young children. It appears that the degree to which a child has developed a RVF/LH advantage for high spatial frequency visual information is associated with the degree to which a child has developed a RVF/LH advantage for letter stimuli. Furthermore, we found significant correlations between children's level of letter identification ability as measured by the CORE Phonics Survey and reaction times to letters and high spatial frequency Gabor patches appearing in the right visual field.

To our knowledge, no other study to date has examined RVF/LH lateralization for high or low spatial frequency Gabor patches in young children. However, a recent paper investigated whether or not a patient with pure alexia would exhibit a deficit in the detection or identification of high spatial frequency Gabor patches (Starrfelt et. al, 2013). This patient, despite a significant reading deficit, did not show any difference in sensitivity to high spatial frequency gratings from control participants. This could be seen as a contradiction to the hypothesis that the processing of high spatial frequency visual information is key for word reading. However, the deficit in pure alexia does not appear to be a deficit in processing the low level visual characteristics of words and letters. The patient in this study, for example, was still able to put letters together in order to accurately read a word, but did so much more slowly, with reduced reaction times as compared to healthy controls (Starrfelt et. al, 2013). This, therefore, appears to be a deficit at a higher level in the visual system than would be affected by spatial frequency. Alexic individuals are able to identify words and letters, and can process words non-holistically, by stringing together their constituent parts (Montant & Behrmann, 2000). This sequential processing approach to reading may be similar to the way an early reader would process words. Sequentially processing words requires intact abilities to process the high spatial frequency visual information that the letters are composed of-it just doesn't require holistic processing of the entire word. The fact that a patient with pure alexia did not show a deficit in the processing of high spatial frequency information does not exclude the possibility that processing of high spatial frequency visual information is necessary for the early development of word and letter processing.

Past studies have, however, investigated RVF/LH lateralization for letter and word stimuli in pre-reading children. Davidoff & Done (1984) conducted a longitudinal study of the visual field advantage for letter matching, and concluded that the right visual field advantage for letters appeared readily as letter knowledge was achieved. This study found a subset of children who could not yet name letters who did not display a RVF/LH advantage, and suggested that this advantage emerges after letter knowledge is achieved. These results are somewhat consistent with our experiment, although in the case of our study, some of the children did have a strong amount of letter knowledge.

It must be noted that when discussing the contribution of HSF bias to the left hemisphere specialization for word reading, we are speaking in particular of the visual aspects of processing a stimulus as complex as a word. It is possible that other aspects of word reading play an equally strong role in its left lateralization, and it may be informative in the future to conduct a study comparing the contribution of these various aspects. For example, Jablonowska & Budhoska (1976) found a RVF/LH lateralization for single letter stimuli in children (age 7) who had developed letter knowledge, but no RVF/LH lateralization for the same stimuli in those same children when they did not yet have letter knowledge. They claim that this has to do with whether or not the material exposed to the children, in this case the letter stimuli, can be constituted as "verbal material", due to the fact that by age 7, the children were able to read and pronounce words from combinations of letters. This provides a slight modification to our hypothesis, wherein the connection between grapheme and phoneme is what drives the RVF/LH advantage for letters. It may be relevant, in future work, to measure not only a score of letter identification and of composite word knowledge, but to include a separate assessment specifically targeting letter sounds, to see whether it is the visual forms themselves or the grapheme to phoneme conversion that plays a larger role in this left hemisphere specialization.

An important limitation to this study that must be addressed is the constantly emerging effect of response (G or H). While these effects were not significant, a general trend emerged in both the spatial frequency and the word conditions in which participants showed a stronger difference in the visual fields for the stimuli when the hand response (G or H) for a given stimulus type was congruent with the side of the screen on which the stimulus appeared. Given the increased reaction times and lower accuracy in the children's data, it is reasonable to conclude that the task was more difficult for them, and a Simmons effect may have been particularly strong. However, because the response to a given stimulus (G or H) was counterbalanced across participants, it is currently impossible to tell whether or not this trend is due to a difference in those participants, or whether it really is a bias due to the response hand. Future studies may benefit from treating the response to a given stimulus as a within subjects variable, so that every participant completes a session responding with both possible patterns. However, given lower executive control abilities in young children, it might prove difficult for the 4 year old participants to appropriately modulate their responses when the pattern switches.

Despite this limitation, it is true that the young children in this study underwent a practice session of the SF task before beginning any of the data collection eventually used in the analysis. This practice session, in theory, should have provided ample time for the effects of response (G or H) to balance out. The practice session also makes it unlikely that the lack of a visual field difference in young children is due to difficulty or discomfort with the task, as is the fact that any child whose accuracy score was below 75% did not have his/her data included in the final analysis. While the sample size of the pre-readers was smaller (N = 15) than that of the adult group (N = 31), the sample size of the group of pre-readers was larger than that of prior papers (Kitterle et. al, 1984, 1990) in which a significant difference in RT and ACC between the two visual fields was detectable. Therefore, it is unlikely that this would be the reason for the lack of visual field difference for high and low spatial frequency Gabor patches in the children's data.

Overall, this study provides further insight into how the hemispheres are organized at different stages of development. The results support the theory that at the age of 4 and 5, before letter identification skills are strong, the hemispheres are not strongly organized based on high or low spatial frequency. It may be the case that high spatial frequency visual information does not contribute to left lateralization for word recognition, but rather that the left lateralization for high spatial frequency visual information is a consequence of reading experience in adults. In the future, it would be informative to further probe this question through a longitudinal study, tracking the development of left lateralization for HSF and for letters over the course of learning to read. Alternatively, a cross sectional design could be applied such that a group of early reading children, ages (7-9) for example, are also tested, in order to investigate to what extent early reading abilities are associated with left lateralization for HSF and letters/words.

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References

Adams, R.J. & Courage, M.L. (2002). Using a single test to measure human contrast sensitivity form early childhood to maturity. *Vision Research 42*: 1205-1210.

Damasio, A.R. (1992). Aphasia. *New England Journal of Medicine 326(8)*: 531-539.

Davidoff, J.B., Done, D.J. (1984). A longitudinal study of the development of visual field advantage for letter matching. *Neuropsychologia 22(3)*: 311-318.

Dehaene, S. & Cohen, L. (2007). Cultural recycling of cortical maps. *Neuron 56*: 384-398.

Diamond, L. & Thorses, B.J. (2008). *Assessing reading: multiple measures.* Arena Press: 2nd Edition.

Dundas, E., Plaut, D.C., Behrmann, M. (2012). The joint development of hemispheric lateralization for words and faces. *Journal of Experimental Psychology: General.* 1-11.

Geschwind, N. (1971). Aphasia. *New England Journal of Medicine 284*: 654-656.

Hsiao, J.H. & Cottrell, G.W. (2009b). What is the cause of left hemisphere lateralization of English visual word recognition? Pre-existing language lateralization, or task characteristics? *Proceedings of the Thirty-First Annual Conference of the Cognitive Science Society.* Mahwah, NJ: Lawrence Erlbaum Associates.

Ivry, R.B. & Robertson, L.C. (1998). *The two sides of perception.* Cambridge, MA: MIT Press

Jablonowska, K., Budhoska, W. (1976). Hemispheric differences in the visual analysis of the verbal and non-verbal material in children. *Acta Neurobiol. Exp 36*: 693-701.

Kitterle, F.L., Christman, S., Hellige, J.B. (1990). Hemispheric differences are found in the identification, but not the detection, of low versus high spatial frequencies. *Perception and Psychophysics 48(4)*: 297-306.

Majaj, N.J., Pelli, D.G., Kurshan, P., Palomares, M. (2002). The role of spatial frequency channels in letter identification. *Vision Research 42*: 1165-1184.

Maurer, U., Brem, S., Bucher, K., Brandeis, D. (2005). Emerging neuropsychological specialization for letter strings. *Journal of Cognitive Neuroscience 17(10)*: 1532-1552.

Mercure, E., Dick, F., Halit, H., Kaufman, J., Johnson, M. (2008). Differential Lateralization for Words and Faces: Category or Psychophysics? *Journal of Cognitive Neuroscience 20(11)*: 2070-2087.

Montant, M. & Behrmann, M. (2000). Pure alexia. *Neurocase 6*: 265-294.

Patterson, K., Kay, J. (1982). Letter-by-letter reading: Psychological descriptions of a neurological syndrome. *Quarterly Journal of Experimental Psychology 34A*: 411-441.

Peyrin, C., Chauvin, A., Chokron, S., Marendaz, C. (2003). Hemispheric specialization for spatial frequency processing in the analysis of natural scenes. *Brain and Cognition 53*: 278-282.

Roberts, D.J., Woollams, A.M., Kim, E., Beeson, P.M., Rapcsak, S.Z., & Lambon Ralph, M.A. (in press). Efficient visual object and word recognition relies on high spatial frequency coding in the left posterior fusiform gyrus: Evidence from a case series of patients with ventral occipito-temporal cortex damage. *Cerebral Cortex.* Doi: 10.1093/cercor/bhs224

Rossion, B., Joyce, C., Cottrell, G., Tarr, M. J. (2003). Early lateralization and orientation tuning for face, word, and object processing in the visual cortex. *NeuroImage 20*: 1609-1624.

Schlaggar, B.L. & McCandliss, B. (2007). Development of neural systems for reading. *Annual Review of Neuroscience 30*: 1-39.

Schlaggar, B.L., Brown, T.T., Lugar, H.M., Visscher, K.M., Miezin, F.M., et. al. (2002). Functional neuroanatomical differences between adults and school age children in the processing of single words. *Science 296*: 1476-1479.

Schneider, W., Eschman, A., Zuccolotto, A. (2002). *E-prime user's guide.* Pittsburgh, PA: Psychology Software Tools.

Seghier, M.L. & Price, C.J. (2011). Explaining left lateralization for words in the ventral occipitotemporal cortex. *The Journal of Neuroscience 31(41)*:14745-14753.

Sergent, J. (1982). The cerebral balance of power: confrontation of cooperation? *Journal of Experimental Psychology 8(2)*: 253-272.

Starrfelt, R., Nielsen, S., Habekost, T., Andersen, T.S. (2013). How low can you go: spatial frequency sensitivity in a patient with pure alexia. *Brain and Language 126*: 188-192.

Szaflarski, J.P., Holland, S.K., Schmithorst, V.J., Byars, A.W. (2006). An fMRI study of language lateralization in children and adults. *Human Brain Mapping 27(3)*: 202-212.

Turkeltaub, P.E., Gareau, L., Flowers, D.L., Zeffiro, T.A., Eden, G.F. (2003). Development of neural mechanisms for reading. *Nature Neuroscience 6*: 767-773.

Warrington, E.K., Shallice, T. (1980). Word form dyslexia. *Brain 103*: 99-112.

Woodhead, Z.V.J., Wise, R.J.S., Sereno, M., Leech, R. (2011). Dissociation of sensitivity to spatial frequency in word and face preferential areas of the fusiform gyrus. *Cerebral Cortex 21(2)*: 2307-2312.