Reading laterally: The cerebral hemispheric use of spatial frequencies in visual word recognition

Karine Tadros
Centre de Recherche en Neuropsychologie Expérimentale et Cognition, Département de Psychologie, Université de Montréal, Montréal, Canada

Nicolas Dupuis-Roy
Centre de Recherche en Neuropsychologie Expérimentale et Cognition, Département de Psychologie, Université de Montréal, Montréal, Canada

Daniel Fiset
Département de Psychoéducation et de Psychologie, Université du Québec en Outaouais, Québec, Canada

Martin Arguin
Centre de Recherche en Neuropsychologie Expérimentale et Cognition, Département de Psychologie, Université de Montréal, Montréal, Canada

Frédéric Gosselin
Centre de Recherche en Neuropsychologie Expérimentale et Cognition, Département de Psychologie, Université de Montréal, Montréal, Canada

It is generally accepted that the left hemisphere (LH) is more capable for reading than the right hemisphere (RH). Left hemifield presentations (initially processed by the RH) lead to a globally higher error rate, slower word identification, and a significantly stronger word length effect (i.e., slower reaction times for longer words). Because the visuo-perceptual mechanisms of the brain for word recognition are primarily localized in the LH (Cohen et al., 2003), it is possible that this part of the brain possesses better spatial frequency (SF) tuning for processing the visual properties of words than the RH. The main objective of this study is to determine the SF tuning functions of the LH and RH for word recognition. Each word image was randomly sampled in the SF domain using the SF bubbles method (Willenbockel et al., 2010) and was presented laterally to the left or right visual hemifield. As expected, the LH requires less visual information than the RH to reach the same level of performance, illustrating the well-known LH advantage for word recognition. Globally, the SF tuning of both hemispheres is similar. However, these seemingly identical tuning functions hide important differences. Most importantly, we argue that the RH requires higher SFs to identify longer words because of crowding.

Keywords: reading, word recognition, spatial frequencies, hemispheric lateralization

Citation: Tadros, K., Dupuis-Roy, N., Fiset, D., Arguin, M., & Gosselin, F. (2013). Reading laterally: The cerebral hemispheric use of spatial frequencies in visual word recognition. *Journal of Vision*, *13*(1):4, 1–12, http://www.journalofvision.org/content/13/1/4, doi: 10.1167/13.1.4.

Introduction

In visual word recognition, lexical, phonological, and semantic knowledge are used to make sense of what we are seeing. But before using such language skills, the human mind needs to extract the visuo-orthographic information in the stimuli (i.e., letters and words). It is well known that many low-level visual properties (e.g., contrast and spatial frequency [SF] content) influence the ease with which someone reads (see, for example, Fiset, Arguin, & Fiset, 2006; Fiset, Gosselin, Blais, & Arguin, 2006; Howell & Kraft, 1960; Legge, Rubin, & Luebker, 1987; Van Nes & Jacobs, 1981). Different SFs are associated with different qualities of visual information. In visual word recognition, for instance, lower SFs give access to coarse word shape but not to fine details, whereas higher SFs give access to fine letter traits but not to coarser word shape. The visual system's ability to perceive different SFs varies according to a contrast sensitivity function (CSF; Campbell & Green, 1965). This function follows an inverted U-shape peaking at about seven cycles per

doi: 10.1167/13.1.4 Received November 10, 2012; published January 4, 2013 ISSN 1534-7362 © 2013 ARVO

degree of visual angle. The optimal SFs for high-level visual categorization (i.e., face identification, word recognition, object categorization) are thought to be those presenting the best balance between the ideal SF information for target discrimination within a stimulus class and the human CSF (Chung, Legge, & Tjan, 2002).

In the past two decades, work on the role of SFs in orthographic processing has focused primarily on letter identification (Alexander, Xie, & Derlacki, 1994; Chung et al., 2002; Chung & Tjan, 2007; Majaj, Pelli, Kurshan, & Palomares, 2002; Solomon & Pelli, 1994). These studies have shown that a relatively narrow band of SFs, between one and three cycles per letter (depending on letter size, whereby readers shift toward higher SFs as letter size increases; Majaj et al., 2002), are most useful for letter identification. Researchers have also started to look into spatial-frequency processing for word recognition (e.g., Chung & Tjan, 2009; Legge, Pelli, Rubin, & Schleske, 1985) and have found an optimal spatial-frequency range quite similar to that of letter recognition.

It is commonly acknowledged that word recognition relies primarily on the left hemisphere (LH) for right-handed individuals. However, the right hemisphere (RH) may also contribute to reading as it is often reported to possess certain, albeit limited, reading skills (see, for example, Brooks, 1973; Bryden & Allard, 1976; Cohen et al., 2003; Coslett & Monsul, 1994; Deason & Marsolek, 2005; Gazzaniga, LeDoux, & Wilson, 1977; Marsolek, Kosslyn, & Squire, 1992; Sidtis, Volpe, Wilson, Rayport, & Gazzaniga, 1981). For instance, normal readers have been found to present an RH advantage for the recognition of words that are handwritten or that are printed in novel or script-type fonts (versus an LH advantage for words printed in standard print-type fonts; Brooks, 1973; Bryden & Allard, 1976; Deason & Marsolek, 2005). What's more, some individuals with brain lesions resulting in impaired reading have been found to rely on the RH for reading. In fact, Coslett and Monsul (1994) studied participants who had an acquired dyslexia following a brain lesion to the LH and further impeded their reading abilities when they applied transcortical magnetic stimulation to inhibit their RH but not when they applied it to inhibit the left. Accordingly, Cohen et al. (2003) found, in readers with acquired letter-by-letter dyslexia, that the RH's fusiform gyrus assumed some of the functional properties normally specific to the LH fusiform gyrus, thus supporting the hypothesis that residual visuo-orthographic processes may take place in the RH. Moreover, the RHs of some split-brain patients (i.e., patients who have undergone a corpus callosotomy) display a wide range of linguistic capacities, ranging from simple semantic matching to competent overt word recognition (such as in patient P.S.; Gazzaniga, LeDoux, & Wilson, 1977; and in patient V.P., Sidtis, Volpe, Wilson, Rayport, & Gazzaniga, 1981). These studies generally support the hypothesis that the visual processing of words by the RH may be useful for word recognition under certain circumstances. However, they also conclude that there is a clear advantage for word processing in the LH, and they underline the possibility that the visual processing of words may differ between the hemispheres.

It has been proposed that the hemispheric differences in reading ability may result from a hemispheric asymmetry in SF processing, with a relative bias for higher SFs in the LH (e.g., Ivry & Robertson, 1998; Kitterle, Christman, & Hellige, 1990; Kosslyn, Chabris, Marsolek, & Koenig, 1992; Sergent, 1982). In particular, the LH superiority in reading would rest on its bias toward the processing of medium-to-high SFs, which appear to be optimal for word recognition.

Many researchers have studied the SF-processing abilities of the cerebral hemispheres. In low-level tasks (typically detection tasks), such as contrast sensitivity measurements, a hemispheric equivalence has typically been found (see, for example, Chiarello, Senehi, & Soulier, 1986; Fendrich & Gazzaniga, 1990; Hardyck, 1991; Peterzell, 1991; Sergent, 1982). However, a number of low-level studies have also shown a prevalence of the RH for SF processing (see Grabowska & Nowicka, 1996, for an exhaustive review). Furthermore, in a recent functional magnetic resonance imaging study, Woodhead, Wise, Sereno, and Leech (2011) found the left occipitotemporal cortex to be more strongly activated than the right occipitotemporal cortex for sinwave gratings of high SFs, and vice versa for sinewave gratings of low SFs.

In high-level tasks (typically identification tasks), such an LH superiority for processing high SFs and an RH superiority for processing low SFs has typically been reported (Grabowska & Nowicka, 1996; Sergent, 1982). Martin (1979) was among the first to show such differences in the processing of relative SFs in normal observers through Navon's hierarchical letter patterns (for instance, a large letter *C* visually composed of smaller letters *A*—here, the energy of the smaller letters *A* is limited to relatively high SFs, whereas the energy of the large letter *C* lies mostly, but not exclusively, in relatively low SFs). She found that relatively higher SFs triggered quicker responses when they were presented to the LH than when they were presented to the right. Inversely, relatively lower SFs led to quicker responses when they were presented to the RH than to the LH. Sergent (1982) came to the same conclusions with a similar task. Later studies directly linked the hierarchical letter patterns to SF content, either by reducing the lower SF content of the stimulus (Hughes, Fendrich, & Reuter-Lorenz, 1990; Lamb & Yund, 1996; Robertson,

1996) or with an adaptation procedure (with sinusoidal gratings of high or low frequency; Shulman, Sullivan, Gish, & Sakoda, 1986). These studies found that advantages attributed to the relatively high or low SFs of the hierarchical letters could be countered by these absolute-frequency alterations, thus linking the two.

However, even in high-level tasks, findings are somewhat divergent. For example, Mercure, Dick, Halit, Kaufman, and Johnson (2008) failed to find an orthogonal modulation of the N170 in the two hemispheres in function of SF content in a word and in a face one-back memory tasks. They did observe, however, an attenuation of the N170 electroencephalographic component in the LH for identifying low-pass filtered words but not for identifying high-pass filtered words.

Although the hemispheres are thought to have specific SF preferences at a low level of processing, the precise SFs privileged by the RH and LH for word recognition remain to be determined. Moreover, the level of processing at which these biases take place remains nebulous (see the General discussion section for a more detailed account on this matter). An SF-related hemispheric specificity would have a great impact on our understanding of information processing in the brain, as it could contribute to a relatively parsimonious account for function attribution. The present study aims to understand SF processing for word recognition in the cerebral hemispheres through lateral visual presentation and has two main goals: first, to determine the SF spectrum used by each cerebral hemisphere for accurate overt word recognition, and second, to determine whether, and how, the low-level processing of SFs for accurate overt word recognition differs between hemispheres.

Issues have been brought forth concerning the use of laterally presented lexical stimuli to study hemispheric differences in reading. It has been suggested that properties specific to word processing are likely to interact with hemifield presentation and that these properties may exert a negative bias for the recognition of words presented to the left visual field (LVF) in comparison to the right visual field (RVF; see, for example, Brysbaert, Vitu, & Schroyens, 1996). In fact, it has been shown that in the French and English languages, the first letter in a four-to-seven-letter word carries the most information value for its accurate identification (e.g., Blais et al., 2009). This letter is the most eccentric in the LVF/RH (and thus has the least visual acuity) and the least eccentric in the RVF/LH (and thus has the best visual acuity). This may impede the ability of the RH to accurately recognize words independently of its actual word-processing ability. However, Bryden and his collaborators have attempted to assess the impact of the locus of information value on performance and found that it failed to influence performance. They concluded that information value does not affect hemispheric asymmetries in visual word recognition (Bryden, 1986; Bryden, Mondor, Loken, Ingleton, & Bergstrom, 1990). Furthermore, a recent study (Tadros, Morin-Duchesne, Arguin, & Gosselin, 2012) goes on to show that there is an actual processing advantage for the initial letters in the LVF despite their greater eccentricity and that performance in the LVF/RH is not disadvantaged by the fact that the initial letters (i.e., the most eccentric) carry more information value. In this context, we deem using laterally presented stimuli appropriate for studying SF use between hemispheres.

In the current study, we employed SF bubbles to determine the SFs used for accurate overt word recognition by the cerebral hemispheres (Thurman & Grossman, 2011; Willenbockel et al., 2010; Willenbockel, Lepore, Nguyen, Bouthillier, & Gosselin, 2012). Each word image will be randomly sampled in the SF domain and presented laterally to the left or right visual hemifield. Following a large number of trials, the SFs correlated with overt word recognition performance can be revealed for each cerebral hemisphere. A key advantage of this method over, for example, low- and high-pass filtering or band-pass filtering methods is that it allows much finer and unbiased SF tuning estimates. Thurman and Grossman (2011) looked at SF tuning for discriminating videos of human actions using SF bubbles as well as a more traditional approach, which consisted of measuring signal-to-noise ratio thresholds for videos filtered by one of six Gaussian band-pass filters. Results from both methods were consistent. However, as the authors concluded,

> "By comparing the data from both experiments, it is clear that one significant advantage of the SF bubbles method over the band-pass filtering method is the resolution of the SF tuning estimates. . . . Another benefit of the SF bubbles method is that all SFs are represented on each trial, just in different proportions, so observers are not able to adapt to particular SF bands during the experiment." (p. 579)

These benefits of the SF bubbles also apply to reverse correlation (e.g., Ahumada & Lovell, 1971). One important difference between these two methods is that the former reveals the visual information that leads to accurate responses—the so-called "potent" information—whereas the latter reveals the visual information that determines responses, accurate and inaccurate—the so-called "represented" information (see Gosselin & Schyns, 2001, 2004; see also Murray & Gold, 2004). Using SF bubbles, we will thus be able to reveal directly, for each visual hemifield, the precise SFs used most accurately for word recognition. To our knowledge, such precise SF tuning estimates have yet to be

Figure 1. Examples of filtered word images that were submitted to a random spatial frequency sampling using the bubbles method. During the experimental task, the quantity of information revealed (i.e., the number of bubbles) varied according to the participant's response accuracy.

performed for word recognition in the cerebral hemispheres.

Methods

Participants

Twelve normal right-handed skilful readers, students at the University of Montreal, took part in the full experiment (seven other participants were excluded following the preselection task described below). All were native French speakers and had normal or corrected-to-normal vision. Participants were preselected on the basis of their right-handedness, as assessed by the Edinburgh Handedness Inventory (Oldfield, 1971), as well as on the basis of their reading abilities for words presented to the right and left visual hemifields (see the Procedure section for more details).

Material and stimuli

The experiment ran on a 2.5-GHz Macintosh computer (model: dual 2.5 GHz PowerPC G5). The experimental program was developed in Matlab (Natick, MA) using functions from the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). Stimuli were displayed on a Sony Trinitron Multiscan G420 monitor measuring 45.4 cm in diagonal, with a resolution of 1024 × 768 pixels and a refresh rate of 100 Hz. The monitor was calibrated to allow a linear manipulation of luminance. The resulting corrected table contained 167 luminance levels, ranging from 0.97 cd/m^2 to 138.67 cd/m^2. The viewing distance was maintained at 49 cm by using a chin rest. Stimuli were lowercase words printed in Arial font size 30 (x-height subtending 0.64° of visual angle). They appeared in black, at 45% of full contrast. They were presented over a medium gray background (halfway between white and black, 68.15 cd/m^2) and were sampled in the SF domain.

The stimuli were word images constructed from a list of four-, five- or six-letter French words. Nine hundred different words were used. Lexical frequency was controlled in this word list. A post hoc analysis looked into the impact of the orthographic neighborhood size of our words and did not find a triple interaction between word length, orthographic neighborhood size, and visual hemifield pertaining to accuracy rates (much like what Lavidor & Ellis, 2002, found). Each word was presented twice to each participant, once to each hemifield, with the order of hemifields counterbalanced across words. Word images were 128 × 128 pixels in size. Their SF content was extracted via fast Fourier transform (FFT) and filtered randomly across trials following the application of SF bubbles by Willenbockel et al. (2010; see Figure 1 for an example of filtered words). In a nutshell, each SF filter was created by first generating a random vector of 4,996 binary elements, following a binomial distribution, with a mean equal to the number of bubbles in the trial. Second, the resulting vector was convolved with a Gaussian kernel that had a standard deviation of 1.6. Third, we scaled the resulting convolved vector according to a logarithmic function that approximates the human visual system's SF sensitivity (see De Valois & De Valois, 1990). This entails that the energy revealed for samples of higher SFs, to which we are less sensitive, was greater than for samples of lower SFs. The resulting convolved and log-scaled vector contained 128 elements representing each SF. Data analyses will be based on the SF vectors. To create the two-dimensional SF-filtered word images, vectors were rotated about their origins and dot-multiplied with the FFT amplitudes. For more details on the SF bubbles method, see Willenbockel et al. (2010).

Stimuli were right aligned (for LH displays) or left aligned (for RH displays) at 1.5° from the locus of ocular fixation—the center of the screen. Therefore, the maximal eccentricities of the letters within our stimuli were approximately 3.8°, 4.4°, and 4.9° of visual angle for words of four, five, and six letters, respectively. A fixation cross was presented at the center of the screen for 570 ms before the word image. The word image then appeared on the screen for 150 ms and was followed by a gray screen that remained until the start of the next trial. The stimuli were presented for a short period of time to minimize the possibility that observers use eye movements to position the word in central vision (Cohen & Ross, 1977; Young, 1982; see also reviews by Alpern, 1962, 1971, and Carpenter, 1977). Nevertheless, because cone receptor density decreases approximately fivefold over the central 2° (Østerberg, 1935), even small shifts from fixation may significantly affect the availability of SF information and thereby influence performance. It has thus been strongly recommended to monitor eye fixations during tasks using lateralized presentations (Jordan, Patching, & Thomas, 2003). Ocular fixations were measured in participants by using the EyeLink II head-mounted eye tracker (SR Research Ltd., Kanata, Ontario, Canada). This system has an average gaze position error of $<0.5°$, a resolution of 1 arc min, and a linear output over the range of the monitor used.

We first attempted to maintain the number of bubbles constant and let word identification accuracy vary across hemispheres (as in Willenbockel et al., 2010). However, word identification accuracy differed so much between the two hemifields that observers either performed perfectly in the right hemifield or at chance in the left hemified. We thus opted to maintain word identification accuracy at 50% for each visual hemifield by independently adjusting the number of bubbles on a trial-by-trial basis using a converging staircases method (Cavanagh & Anstis, 1991). These staircases start at performance extremes (i.e., where the minimal and maximal quantity of bubbles presented are 5 and 45, respectively) and then converge toward the number necessary to maintain a threshold of 50%. Implications of this paradigm decision will be considered in the General discussion section.

Procedure

Preselection task

Reading ability was measured through response accuracy and reading latency for full-contrast unfiltered words presented at 1.5° visual angle eccentricity to the left and right visual hemifields. The word list used for this preselection was made of French four- to seven-letter words that were not used in the experimental task. Our purpose in submitting participants to a preselection task was threefold. First, we wanted to ensure that the response times of participants for words presented to the LH (i.e., the right visual hemifield) did not vary as a function of word length. Indeed, normal readers do not show a word length effect (i.e., increasing reading latency with the number of letters in the word) for words presented to the right hemifield, but they usually do for words presented to the left hemifield (Bub & Lewine, 1988; Lavidor & Ellis, 2002; variations of reading latency as a function of word length for the RH were not considered for participant selection as they may interact with reading accuracy). Second, we wanted to make sure that accuracy dropped with increasing word length for words presented to the RH (left visual hemifield), as is typically encountered in normal readers. Satisfying these criteria confirms that the participants' brain regions specialized in language processing are well lateralized to the LH. Third, we wanted to ensure a sufficient baseline accuracy level. Our accuracy threshold was 80% correct for the easiest condition of the preselection task (four-letter words presented to the right hemifield). In the experimental task, the number of SF bubbles (i.e., the quantity of information) presented in each word was varied to maintain a 50% success rate. The lower the success rate, the greater the quantity of SFs presented in the word images. However, the more different SFs were presented in a word image, the less this word allowed for discrimination of SF use (as a larger variety is presented and it becomes more difficult to dissociate the SFs used to respond correctly or incorrectly). It is for this reason that we required a relatively high baseline accuracy, which allows significant variations in SF filtering (vs. a participant with a low baseline, who would require a larger number of SF bubbles to maintain a 50% success rate). Following this preselection task, 7 participants were excluded and 12 were retained for the full experimental task. Most of the participants who were excluded did not satisfy the third criterion, their baseline accuracy level being too low to allow for appropriate variations in SF filtering.

Experimental task

Each participant underwent 1,800 trials. The experiment was divided into 12 blocks of 150 trials each. Participants wore the eye-tracker helmet, and a calibration of eye fixations was conducted at the beginning of each session (and once every maximum 41 trials thereafter) using a nine-point fixation procedure as implemented in the EyeLink API software (see the EyeLink Manual for details). The calibration was then validated with the EyeLink API software and repeated when necessary until the optimal calibration criterion was reached. Every five trials, participants were instructed to fixate a dot at the center of the screen

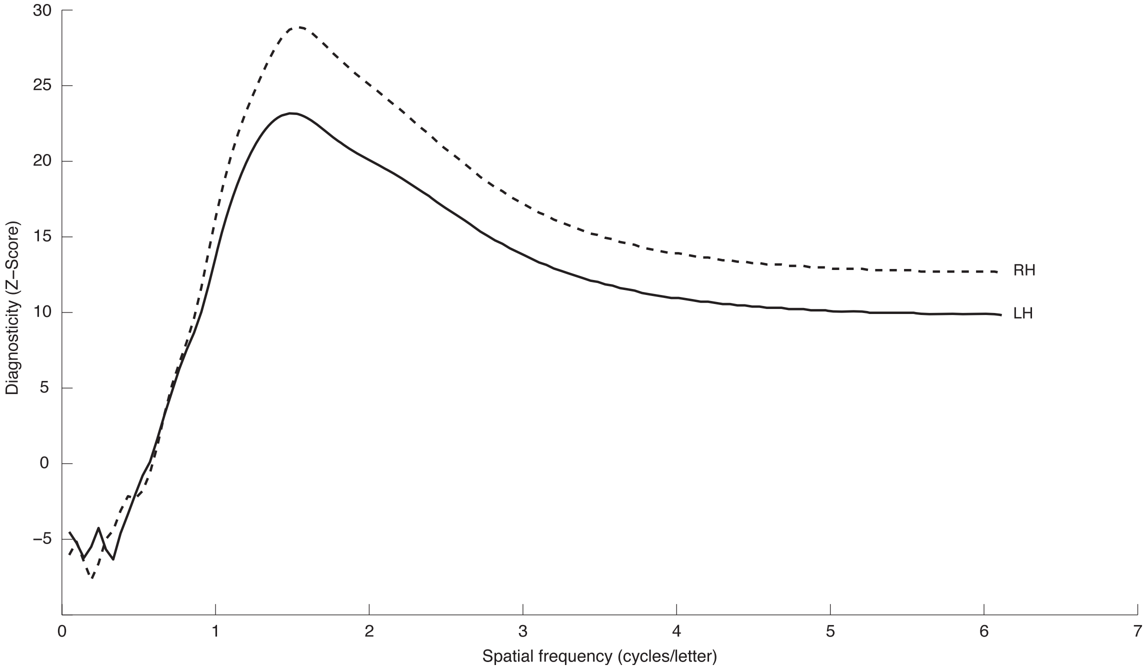

Figure 2. Diagnosticity of spatial frequencies for word recognition with stimuli presented to the two hemispheres.

for an automatic drift correction. During the trials, they were asked to maintain their gaze at the center of the screen at all times, as indicated by a fixation cross. The reader had no prior information as to the location (left or right) of the target word, which was selected randomly for each trial. After each stimulus presentation, the participant was asked to identify the word as accurately as possible. The experimenter, present in the room but out of sight of the participant, typed into the computer the response given and spelled out on every trial. He then triggered the next trial. Participants received no feedback on their performance.

Results

An average of 87% of trials (SD = 9.6%) per participant met the eye-movement acceptance criteria: less than 1.5° of visual angle away from the fixation cross on the x-axis and less than 0.5° of visual angle shift on the x-axis between the first half and the last half of stimulus presentation. Group results were very robust to changes in these criteria. The following results were obtained using these accepted data. As expected, performance was poorer for words presented to the RH than for words presented to the LH. We measured performance by comparing the quantity of information (i.e., the number of bubbles) necessary to maintain a 50% accuracy rate. Words presented to the RH required a greater quantity of information ($M = 20.80$ bubbles, $SD = 2.79$ bubbles) for accurate recognition than those presented to the LH ($M = 15.84$ bubbles, $SD = 2.41$), $t(11) = 6.95$, $p < 0.001$, $d = 2.06$.

To determine the SFs that contribute most to word recognition in each cerebral hemisphere, we performed least-square multiple linear regressions between response accuracies and the random binary vectors used (see the Methods section) separately for each hemisphere and each participant. More specifically, we summed the random binary vectors weighted by the corresponding response accuracies. Then we convolved the resulting vector of regression coefficients with a Gaussian kernel having a full width at half-maximum (FWHM) equal to 2.3548 elements, standardized it according to a Bootstrap procedure (Efron & Tibshirani, 1994; Varian, 2005), and finally log-scaled it (for more details, see Willenbockel et al., 2010). The resulting vector—henceforth referred to as the classification vector—is composed of 128 regression coefficients that indicate the correlation between each SF and its corresponding response accuracy. We also computed group classification vectors for each hemisphere by summing all individual classification vectors and dividing the resulting vector by $\sqrt{n}$ (where $n = 12$, i.e., the number of participants). The z-scored and smoothed group classification vectors are shown in Figure 2. Individual and group results were very similar within hemispheres (average $r = .94$; $SD = .034$) when comparing individual classification vectors with the group vectors for each hemifield, so we report only group results. Note that the right tails of the curves are a consequence of two things: the diagnosticity of

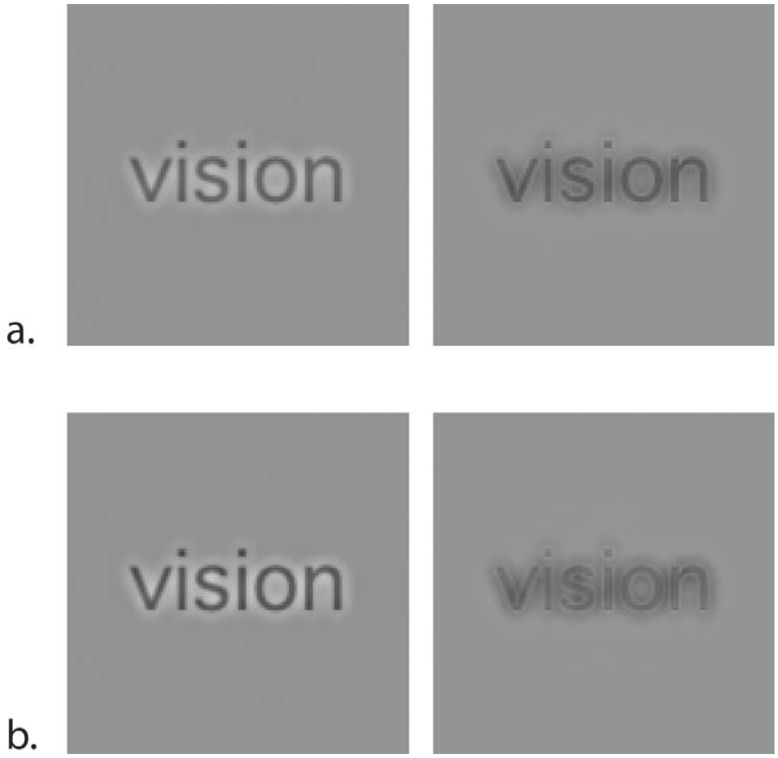

Figure 3. Illustration of the most (left) and least (right) used spatial frequencies for accurate word recognition with stimuli presented to the (a) left and (b) right visual hemifields by filtering the word *vision*.

relatively high SFs for word reading and the coarseness of our sampling of these SFs.

The important SFs for the task at hand were revealed by their divergence from zero. A pixel test (Chauvin, Worsley, Schyns, Arguin, & Gosselin, 2005) was applied to the classification vectors of each cerebral hemisphere to expose the SFs underlying accurate word recognition for each hemisphere ($S_r = 128$, FWHM $= 2.3548$, $p < 0.05$; LH: $Z_{max} = 29.69$, $Z_{crit} = 3.37$; RH: $Z_{max} = 22.68$, $Z_{crit} = 3.37$). We measured the SF peaks by proceeding to a 50% area spatial frequency measure (ASFM; analogous to a 50% area latency measure commonly used in electroencephalography analysis) to the classification vector. This 50% ASFM is a better measure of the central tendency than absolute peaks would be in our experiment because it is less sensitive to the shape of the tuning curve, which was probably distorted by our sampling procedure.

The area taken into account in the 50% ASFM was the area above the very high SFs tail present in the classification vector and considered to be an artifact of the method. The significantly used SF band for words presented to the LH peaked at 2.07 cycles/letter and was 2.33 octaves wide. For words presented to the RH, the significantly used SF band peaked at 2.00 cycles/letter and was 2.90 octaves wide. Hence, optimal tuning was essentially the same for both hemispheres (accordingly, peaks did not differ statistically when data were compared within participants). An illustration of the SFs most and least useful for word identification for words presented to the RH and LH can be seen on the word *vision* in Figure 3a and b. Furthermore, it is clear that the SF tuning functions of both hemispheres have the same shape, the LH's appearing as a simple upward translation of that of the right. Accordingly, z-scores corresponding to the 50% ASFM of the classification vectors are significantly higher for words presented to the LH than for words presented to the RH (z-score average of 8.86 and 6.45, respectively), $t(11) = 3.925$, $p < 0.005$, $d = 1.32$, but the functions remain very strongly correlated to one another ($r = .997$).

Recognition accuracy for both hemispheres decreased with increasing word length,[1] $F(2, 22) = 86.30$, $p < 0.001$, $\eta^2 = .89$. Moreover, this word-length effect was greater for words presented to the RH (mean accuracy of four-letter words = 62%, mean accuracy of six-letter words = 42%; mean difference = 20%, $SD = 6\%$) than for words presented to the LH (mean accuracy of four-letter words = 55%, mean accuracy of six-letter words = 48%; mean difference = 8%, $SD = 5\%$), $F(1, 11) = 26.10$, $p < 0.001$, $\eta^2 = .70$.

We also looked into SF tuning as a function of word length and hemisphere. Once again, individual and group results were very similar within word lengths and hemispheres (average $r = .87$ when comparing individual and group classification vectors), so we report only group results. We compiled the SF tuning functions for word lengths and hemispheres separately by proceeding

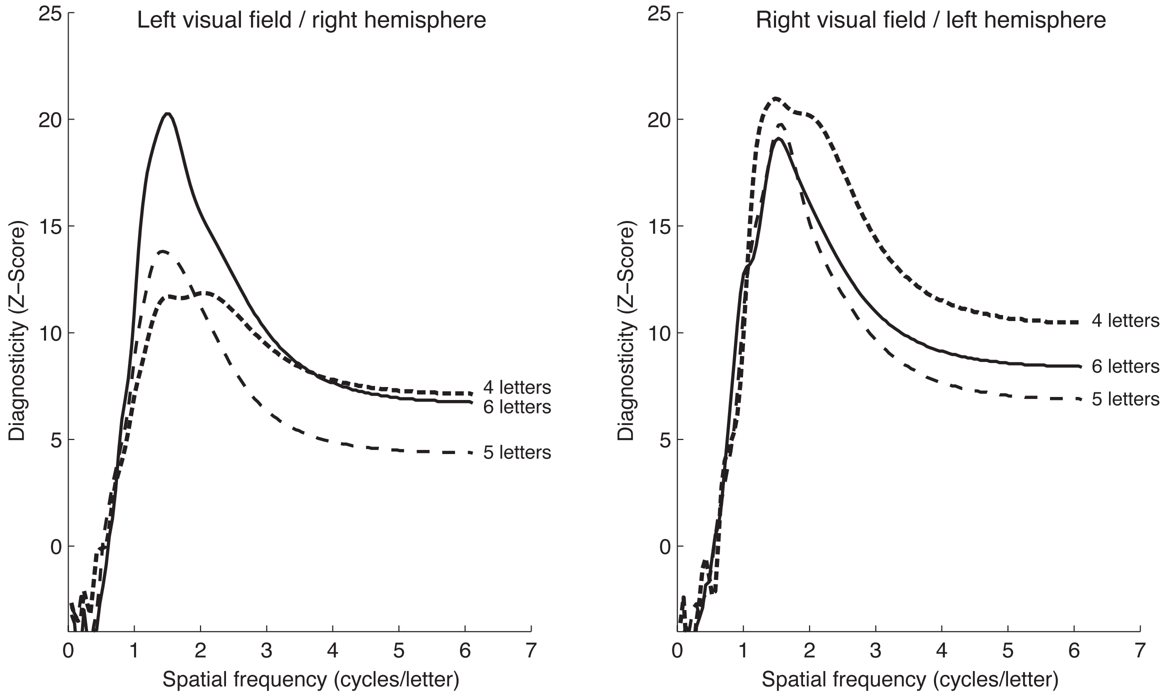

Figure 4. Diagnosticity of spatial frequencies for word recognition as a function of hemisphere and word length.

to separate multiple linear regressions and pixel tests for each word length and each hemisphere ($S_r = 128$, FWHM = 2.3548, $p < 0.05$; LH, four letters: $Z_{\max} = 21.00$, $Z_{\text{crit}} = 3.36$, five letters: $Z_{\max} = 21.16$, $Z_{\text{crit}} = 3.37$, six letters: $Z_{\max} = 20.85$, $Z_{\text{crit}} = 3.37$; RH, four letters: $Z_{\max} = 12.68$, $Z_{\text{crit}} = 3.34$, five letters: $Z_{\max} = 18.88$, $Z_{\text{crit}} = 3.37$, six letters: $Z_{\max} = 12.62$, $Z_{\text{crit}} = 3.38$). The resulting SF tuning functions are presented in Figure 4. The 50% ASFM computed from the individual classification vectors shifted significantly toward higher SFs as word length increased for words presented to the RH, $F(1, 11) = 6.049$, $p < 0.01$, $\eta^2 = .36$ (four letters: $M = 3.21$, $SD = 1.29$; five letters: $M = 4.12$, $SD = 0.94$; six letters: $M = 4.18$, $SD = 1.07$), but not for words presented to the LH, $F(1, 11) = 1.270$, $p = 0.3$, $\eta^2 = .10$ (four letters: $M = 4.40$, $SD = 1.61$; five letters: $M = 4.93$, $SD = 1.26$; six letters: $M = 5.91$, $SD = 1.53$). In the RH, tuning was biased toward significantly higher SFs for words of six letters compared with words of four letters, $t(11) = 2.99$, $p < 0.01$, $d = 3.94$, and five letters, $t(11) = 2.47$, $p < 0.05$, $d = 3.22$. This shift in tuning implies that for longer words (which also had greater mean eccentricities in our study), the RH needed to access higher SFs for accurate identification than for shorter words.

General discussion

The goal of the present study was to uncover the SF tuning patterns for word recognition in each cerebral hemisphere and, importantly, whether they differed from one another. To do so, we presented word images randomly filtered in the SF domain to the LH or to the RH. As expected, performance, as measured by the number of bubbles required to reach target word identification accuracy overall, was poorer for words presented to the RH than for words presented to the LH. Furthermore, word identification accuracy correlated negatively with word length in both hemispheres but especially more so for words presented to the RH. It has long been known that string length has a greater impact on visual word recognition when letter strings are presented to the RH than when they are presented to the LH (Bouma, 1973; Ellis, Young, & Anderson, 1988; Melville, 1957; Young & Ellis, 1985). In fact, the LH often does not exhibit a word-length effect at all. However, Fiset et al. (2006) have shown that removing SFs from words presented foveally, especially high SFs, produces strong word-length effects. Therefore, we are not surprised to find a word-length effect in the LH as well.

The SFs most correlated with accurate recognition were determined for each hemisphere and according to word length. Our main finding is that the SF tuning peaks for words presented to the LH and to the RH when all word lengths were collated are essentially the same and are located at approximately two cycles/letter (for letters with an x-height subtending 0.64° of visual angle). This entails that words presented to the RH are identified most accurately when using the same visual information as words presented to the LH (as long as the appropriate interhemispheric communication is possible, of course). Hence, our results do not support the hypothesis that the RH is biased toward lower SFs than the LH. The SF tuning we obtained for words lateralized to one hemisphere or the other does match the SF tuning recently reported for words presented centrally and at vertical eccentricity (Chung & Tjan, 2009). In fact, our tuning peaks fall right on the functions of peak tuning frequency for reading by letter print size that these authors obtained, both for words presented at the fovea and for words presented at vertical eccentricity.

We do, however, find important variations in SF use when we take a closer look at our data. A first hemispheric difference we observe in the present study is that even though the peak SFs are the same for both hemispheres, the height of these peaks was greater in the LH than in the RH. This finding could have resulted from an artifactual cause. The least-square multiple linear regressions that we perform give rise to the greatest z-scores when the number of bubbles is such that half the search space is sampled, everything else being equal. Put differently, if the sampling of the words presented to the LH was closer to this optimal sampling than that of the words presented to the RH, we would expect to find higher peaks in the LH than in the RH, which could, in turn, have explained the effect we observe in our results with regard to these peaks. Quite to the contrary, however, we find the RH was presented stimuli with more optimal SF sampling. This renders our empirical observation even more surprising because despite the asymmetrical sampling, which favors the regressions performed on RH data, we see higher peaks in the LH than in the RH. We believe this could have resulted from the LH being more consistent in its use of SFs than the RH. That is, the SFs found to be most useful for word recognition would lead more often to accurate identification in the LH than in the RH. In turn, this could mean that, at some level of visual processing, one or many factor(s) intervene(s) to increase the relative consistency of the LH. One plausible explanation pertains to the contribution of top-down processes on word recognition. The LH would possess more of these top-down interactions for word processing than the RH, possibly because it is the hemisphere responsible for overt word recognition. Consequently, the LH would be able to better target the diagnostic SFs through top-down feedback.

The most important hemispheric difference we find in our data is a shift toward the use of higher SFs for longer words presented to the RH but not to the LH. As we mentioned above, more bubbles were required in the RH than in the LH to reach target performance. Therefore, we cannot rule out entirely that this difference between the stimuli presented to the two hemispheres is somehow responsible for the shift toward higher SFs in the RH. However, we believe this is unlikely because, were it the case, the hemisphere submitted to the most impoverished words would be most affected—and we observe the exact opposite. Rather, we believe that this shift in SF use as a function of word length may reflect the RH's attempt to diminish the impact of visual crowding.

Letters closer together than a critical spacing are seen as an unidentifiable jumble—they are "crowded" (e.g., Bouma, 1970; Pelli et al., 2007; and see Whitney & Levi, 2011, for a recent review of findings on crowding). Chung and Tjan (2007) observed a small shift toward using higher SFs when presenting highly crowded letters, much like we observe with increased word length. One reason for this shift may be that higher frequencies give a finer discrimination of the different features composing the letters in the word. But why would crowding increase with word length? The mean eccentricity of letters increased with word length in our experiment so that the most eccentric letters were at approximately 4.9° of visual angle for six-letter words and at approximately 3.8° of visual angle for four-letter words. The so-called "Bouma law" states that the critical spacing between letters is roughly half the eccentricity (Bouma, 1970). In other words, crowding increases with eccentricity and, in our experiment, with word length. There is one more aspect of our finding that remains to be explained by this crowding hypothesis: Why don't we observe a similar shift in SF use in the LH? The visual span, which is defined qualitatively as the number of letters in a nonsensical string of letters that can be recognized reliably without moving the eyes, is known to be largely determined by crowding, and this visual span is usually compressed in the left hemifield relatively to the right (Legge et al., 2007). This suggests that the RH is subject to more crowding than the LH, at least when processing letters. Obviously, more research will be necessary to put this hypothesis to the test.

Acknowledgments

We thank the participants who collaborated to this demanding experiment. The following financial support is acknowledged: A grant from the Canadian Institutes for Health Research to Martin Arguin and Frédéric Gosselin. Karine Tadros and Nicolas Dupuis-Roy are supported by a graduate scholarship from the Fonds Québécois de Recherche en Nature et Technologies (FQRNT).

Commercial relationships: none.

Corresponding author: Frédéric Gosselin.
Email: frederic.gosselin@umontreal.ca.
Address: Département de psychologie, Université de Montréal, Montréal, QC, Canada.

Footnote

[1] Remember that accuracy was maintained at 50**%** for each hemisphere without regard to word length. Thus, accuracy was allowed to vary as a function of word length within each hemisphere.

References

Ahumada, A. J., & Lovell, J. (1971). Stimulus features in signal detection. *Journal of the Acoustical Society of America, 49,* 1751–1756.

Alexander, K. R., Xie, W., & Derlacki, D. J. (1994). Spatial-frequency characteristics of letter identification. *Journal of the Optical Society of America, 11,* 2375–2382.

Alpern, M. (1962). Muscular mechanisms. In H. Davson (Ed.), *The eye* (Vol. 3). New York: Academic Press.

Alpern, M. (1971). Effector mechanisms in vision. In J. A. Kling & L. A. Riggs (Eds.), *Woodworth and Schlosberg's experimental psychology* (3rd ed.). New York: Holt, Rinehart & Winston.

Blais, C., Fiset, D., Jolicoeur, P., Arguin, M., Bub, D., & Gosselin, F. (2009). Reading between eye saccades. *PLoS ONE,* 4(7), e6448, doi:10.1371/journal.pone.0006448.

Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature, 226,* 177–178.

Bouma, H. (1973). Visual interference in the parafoveal recognition of initial and final letters of words. *Vision Research, 13,* 767–782.

Brainard, D. H. (1997). The psychophysics toolbox. *Spatial Vision, 10,* 433–436.

Brooks, L. R. (1973). Treating verbal stimuli in a novel manner. Paper presented at the Eastern Psychological Association Meetings, April, 1973, Washington, D. C.

Bryden, M. P. (1986). On the possible dangers of using horizontal word displays in visual field studies. *Brain and Cognition, 5*(3), 362–378.

Bryden, M. P., & Allard, F. (1976). Visual field differences depend on typeface. *Brain and Language, 3,* 191–200.

Bryden, M. P., Mondor, T. A., Loken, M., Ingleton, M. A., & Bergstrom, K. (1990). Locus of information in words and the right visual field effect. *Brain and Cognition, 14*(1), 44–58.

Brysbaert, M., Vitu, F., & Schroyens, W. (1996). The right visual field advantage and the optimal viewing position effect: On the relation between foveal and parafoveal word recognition. *Neuropsychology, 10*(3), 385.

Bub, D. N., & Lewine, J. (1988). Different modes of word recognition in the left and right visual fields. *Brain and Language, 33,* 161–188.

Campbell, F. W., & Green, D. G. (1965). Optical and retinal factors affecting visual resolution. *The Journal of Physiology, 181*(3), 576.

Carpenter, R. H. S. *Movements of the eyes*. London: Peon, 1977.

Cavanagh, P., & Anstis, S. M. (1991). The contribution of color to motion in normal and color-deficient observers. *Vision Research, 31,* 2109–2148.

Chauvin, A., Worsley, K. J., Schyns, P. G., Arguin, M., & Gosselin, F. (2005). Accurate statistical tests for smooth classification images. *Journal of Vision, 5*(9):1, 659–667, http://www.journalofvision.org/content/5/9/1, doi:10.1167/5.9.1. [PubMed] [Article]

Chiarello, C., Senehi, J., & Soulier, M. (1986). Viewing conditions and hemispheric asymmetry for the lexical decision. *Neuropsychologia, 24,* 521–529.

Chung, S. T. L., Legge, G. E., & Tjan, B. S. (2002). Spatial-frequency characteristics of letter identification in central and peripheral vision. *Vision Research, 42,* 2137–2152.

Chung, S. T. L., & Tjan, B. S. (2007). Shift in spatial scale in identifying crowded letters. *Vision Research, 47,* 437–451.

Chung, S. T., & Tjan, B. S. (2009). Spatial-frequency and contrast properties of reading in central and peripheral vision. *Journal of Vision, 9*(9):16, 1–19, http://www.journalofvision.org/content/9/9/16, doi:10.1167/9.9.16. [PubMed] [Article]

Cohen, L., Martinaud, O., Lemer, C., Lehericy, S., Samson, Y., Obadia, M., et al. (2003). Visual word recognition in the left and right hemispheres: Anatomical and functional correlates of peripheral alexia. *Cerebral Cortex, 13,* 1313–1333.

Cohen, M. E., & Ross, L. E. (1977). Saccade latency in children and adults: Effects of warning interval and target eccentricity. *Journal of Experimental Child Psychology, 23,* 539–549.

Coslett, H. B., & Monsul, N. (1994). Reading with the right hemisphere: Evidence from transcranial magnetic stimulation. *Brain and Language, 46,* 198–211.

Deason, R. G., & Marsolek, C. J. (2005). A critical boundary to the left-hemisphere advantage in word processing. *Brain and Language, 92,* 251–261.

De Valois, R., & De Valois, K. (1990). *Spatial vision.* New York: Oxford University Press.

Efron, B., & Tibshirani, R. J. (1994). *An introduction to the bootstrap.* Boca Raton, FL: CRC Press.

Ellis, A. W., Young, A. W., & Anderson, C. (1988). Modes of word recognition in the left and right cerebral hemispheres. *Brain and Language, 35,* 254–273.

Fendrich, R., & Gazzaniga, M. (1990). Hemispheric processing of spatial frequencies in two commissurotomy patients. *Neuropsychologia, 28,* 657–663.

Fiset, S., Arguin, M., & Fiset, D. (2006). An attempt to simulate letter-by-letter dyslexia in normal readers. *Brain and Language, 98,* 251–263.

Fiset, D., Gosselin, F., Blais, C., & Arguin, M. (2006). Inducing letter-by-letter dyslexia in normal readers. *Journal of Cognitive Neuroscience, 18,* 1466–1476.

Gazzaniga, M. S., LeDoux, J. E., & Wilson, D. H. (1977). Language, praxis, and the right hemisphere: Clues to some mechanisms of consciousness. *Neurology, 27,* 1144–1147.

Gosselin, F., & Schyns, P. G. (2001). Bubbles: A technique to reveal the use of information in recognition. *Vision Research, 41,* 2261–2271.

Gosselin, F., & Schyns, P. G. (2004). No troubles with Bubbles: A reply to Murray and Gold. *Vision Research, 44,* 471–477.

Grabowska, A., & Nowicka, A. (1996). Visual-spatial-frequency model of cerebral asymmetry: A critical survey of behavioral and electrophysiological studies. *Psychological Bulletin, 120*(3), 434.

Hardyck, C. (1991). Shadow and substance: Attentional irrelevancies and perceptual constraints in the hemispheric processing of language stimuli. In F. L. Kitterle (Ed.), *Cerebral laterality: Theory and research* (pp. 133–153). Hillsdale, NJ: Lawrence Erlbaum.

Howell, W., & Kraft, C. (1960). *Size, blur, and contrast as variables affecting the legibility of alphanumeric symbols on radar-type displays.* WADC Technical Report, 59-536, Wright-Patterson AFB, Ohio.

Hughes, H. C., Fendrich, R., & Reuter-Lorenz, P. A. (1990). Global versus local processing in the absence of low spatial frequencies. *Journal of Cognitive Neuroscience, 2,* 272–282.

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

Jordan, T. R., Patching, G. R. & Thomas, S. M. (2003). Assessing the role of hemispheric specialization, serial-position processing, and retinal eccentricity in lateralized word recognition. *Cognitive Neuropsychology, 20,* 49–71.

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. *Attention, Perception, & Psychophysics, 48*(4), 297–306.

Kosslyn, S. M., Chabris, C. F., Marsolek, C. J., & Koenig, O. (1992). Categorical versus coordinate spatial relations: Computational analyses and computer simulations. *Journal of Experimental Psychology: Human Perception and Performance, 18*(2), 562.

Lamb, M. R., & Yund, E. W. (1996). Spatial frequency and attention: Effect of level-, target-, and location-repetition on the processing of global and local forms. *Perception & Psychophysics, 58,* 363–373.

Lavidor, M., & Ellis, A. W. (2002). Word length and orthographic neighbourhood size effects in the right and left cerebral hemispheres. *Brain and Language, 80*(1), 45–62.

Legge, G. E., Cheung, S.-H., Yu, D., Chung, S., Lee, H.-W., & Owens, D. (2007). The case for the visual span as a sensory bottleneck in reading. *Journal of Vision, 7*(2):9, 1–15, http://www.journalofvision.org/content/7/2/9, doi:10.1167/7.2.9. [PubMed] [Article]

Legge, G. E., Pelli, D. G., Rubin, G. S., & Schleske, M. M. (1985). Psychophysics of reading: I. Normal vision. *Vision Research, 25,* 239–252.

Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading V: The role of contrast in normal vision. *Vision Research, 27,* 1165–1177.

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.

Marsolek, C. J., Kosslyn, S. M., & Squire, L. R. (1992). Form-specific visual priming in the right cerebral hemisphere. *Journal of Experimental Psychology: Learning, Memory, and Cognition*, *18*(3), 492.

Martin, M. (1979). Hemispheric specialization for local and global processing. *Neuropsychologia, 17,* 33–40.

Melville, J. P. (1957). Word-length as a factor in differential recognition. *American Journal of Psychology, 70,* 316–318.

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*, 2070–2087.

Murray, R. F., & Gold, J. M. (2004). Troubles with bubbles. *Vision Research, 44,* 461–470.

Oldfield, R. C. (1971). The assessment and analysis of handedness: The Edinburgh inventory. *Neuropsychologia, 9,* 97–113.

Østerberg, G. A. (1935). Topography of layer rods and cones in the human retina. *Acta Ophthalmology (Suppl.), 6,* 1–102.

Pelli, D. G. (1997). The Video Toolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision, 10,* 437–442.

Pelli, D. G., Tillman, K. A., Freeman, J., Su, M., Berger, T. D., & Majaj, N. J. (2007). Crowding and eccentricity determine reading rate. *Journal of Vision, 7*(2):20, 1–36, http://www.journalofvision.org/content/7/2/20, doi:10.1167/7.2.20. [PubMed] [Article]

Peterzell, D. H. (1991). On the nonrelationship between spatial frequency and cerebral hemispheric competence. *Brain & Cognition, 15,* 62–68.

Robertson, L. C. (1996). Attentional persistence for features of hierarchical patterns. *Journal of Experimental Psychology: General, 125,* 227–249.

Sergent, J. (1982). Theoretical and methodological consequences of variations in exposure duration in visual laterality studies. *Perception and Psychophysics, 3*(1), 451–461.

Sidtis, J. J., Volpe, B. T., Wilson, D. H., Rayport, M., & Gazzaniga, M. S. (1981). Variability in right hemisphere language function after callosal section: Evidence for a continuum of generative capacity. *The Journal of Neuroscience, 1*(3), 323–331.

Shulman, G. L., Sullivan, M. A., Gish, K., & Sakoda, W. J. (1986). The role of spatial frequency channels in the perception of local and global structure. *Perception, 15,* 259–279.

Solomon, J. A., & Pelli, D. G. (1994). The visual filter mediating letter identification. *Nature, 369,* 395–397.

Tadros, K., Morin-Duchesne, X., Arguin, M., & Gosselin, F. (2012, February). The Letter processing strategy for reading is invariant across the cerebral hemispheres. Presented at the 40th Annual International Neuropsychological Society Meeting, Montreal, Canada.

Thurman, S. M., & Grossman, E. D. (2011). Diagnostic spatial frequencies and human efficiency for discriminating actions. *Attention, Perception & Psychophysics, 73,* 572–580.

Van Nes, F. L., & Jacobs, J. C. (1981). The effects of contrast on letter and word recognition. *IPO Annual Progress Report, 16,* 72–80.

Varian, H. (2005). Bootstrap tutorial. *Mathematica Journal, 9,* 768–775.

Whitney, D., & Levi, D. (2011). Visual crowding: A fundamental limit on conscious perception and object recognition. *Trends in Cognitive Science, 15,* 160–168.

Willenbockel, V., Fiset, D., Chauvin, A., Blais, C., Arguin, M., Tanaka, J., et al. (2010). Does face inversion change spatial frequency tuning? *Journal of Experimental Psychology: Human Perception and Performance, 36,* 122–135.

Willenbockel, V., Lepore, F., Nguyen, D. K., Bouthillier, A., & Gosselin, F. (2012). Spatial frequency tuning during the conscious and non-conscious perception of emotional facial expressions—An Intracranial ERP study. *Frontiers in Psychology, 3,* 237, doi:10.3389/fpsyg.2012.00237.

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

Young, A. (1982). Methodological theoretical bases of visual hemifield studies. In: J. G. Beaumont (Ed.), *Divided visual field studies of cerebral organization* (pp. 11–27). New York: Academic Press.

Young, A. W., & Ellis, A. W. (1985). Different methods of lexical access for words presented to the left and right visual hemifields. *Brain and Language, 24,* 326–358.