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A critical boundary to the left-hemisphere advantage in visual-word processing

Rebecca G. Deason*, Chad J. Marsolek

Department of Psychology, University of Minnesota, 75 East River Road, Minneapolis, MN 55455, USA

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Abstract

Two experiments explored boundary conditions for the ubiquitous left-hemisphere advantage in visual-word recognition. Subjects perceptually identified words presented directly to the left or right hemisphere. Strong left-hemisphere advantages were observed for UPPERCASE and lowercase words. However, only a weak effect was observed for AlTeRnAtInG-cAsE words, and a numerical reversal of the typical left-hemisphere advantage was observed for words in a visual prototype font (a very unfamiliar word format). Results support the theory that dissociable abstract and specific neural subsystems underlie visual-form recognition and fail to support the theory that a visual lexicon operates in the left hemisphere.

Keywords: Functional hemispheric asymmetries; Letter case; Case alternation; Word recognition; Categories; Exemplars

1. Introduction

One of the most well-established findings in neuropsychology is that visual words are processed more effectively when they are presented directly to the left cerebral hemisphere than to the right (e.g., Babkoff, Faust, & Lavidor, 1997; Beaumont, 1982; Bradshaw & Nettleton, 1983; Bub & Lewine, 1988; Burgund & Marsolek, 1997; Chiarello, 1985, 1988; Ellis, Young, & Anderson, 1988; Eviatar, Menn, & Zaidel, 1990; Fiset & Arguin, 1999; Hines, 1978; Jordan, Redwood, & Patching, 2003; Koenig, Wetzel, & Caramazza, 1992; Krueger, 1975; Lambert & Beaumont, 1983; Lavidor & Ellis, 2001; Lavidor, Ellis, & Pansky, 2002; Leiber, 1976; Liu, Chiarello, & Quan, 1999; Schmuller & Goodman, 1979; Young, Ellis, & Bion, 1984; Young & Ellis, 1985; for a review, see Chiarello, Liu, & Shears, 2001). The most common interpretation of this phenomenon is that lexical access and language processing in general are accomplished more effectively in the left hemisphere than in the right, but this explanation is not without competition. Exploring the boundary conditions of the consistently demonstrated left-hemisphere advantage may help to determine what underlies the effect. A useful variable for exploring such boundary conditions may be the familiarity of visual formats for word presentation. A word presented in an unfamiliar visual format can be associated with the same phonological and semantic information as it would when presented in a more familiar form, but the visual processing may differ depending on the formats. Could the left-hemisphere advantage in word recognition be eliminated with the use of an unfamiliar visual format?

One prediction is that the left-hemisphere advantage should be eliminated when words are presented in an unfamiliar format. By unfamiliar format, we mean when words are displayed in such a manner that they take the shape of unfamiliar wholes (i.e., forms that—in terms of their entire holistic configurations—are unlikely to have been viewed before). This can create a situation in which

* Corresponding author. Fax: 1-612-624-2079.
E-mail address: deas0007@umn.edu (R.G. Deason).
URL: http://levels.psych.umn.edu.

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processing in the right hemisphere is relatively more advantaged than when the stimuli are not unfamiliar wholes. This prediction comes from an abstract/specific neural subsystems theory.

Dissociable neural subsystems appear to operate asymmetrically to underlie visual-form recognition (Marsolek, 1995, 1999, 2004; Marsolek, Kosslyn, & Squire, 1992; for a review, see Marsolek & Burgund, 1997). An abstract-category subsystem recognizes the visual-form category to which an input belongs (e.g., the visual-form category for band/BAND) and operates more effectively than a specific-exemplar subsystem in the left cerebral hemisphere. In contrast, a specific-exemplar subsystem recognizes the visual exemplar to which an input form corresponds (e.g., the exemplar for "band" which is different from the exemplar for "BAND") and operates more effectively than an abstract-category subsystem in the right cerebral hemisphere.

According to this theory, left-hemisphere advantages are observed typically in visual-word processing studies using familiar stimuli because an abstract subsystem operates effectively in the left hemisphere and most word processing tasks require the participant to recognize the abstract category of an input (e.g., what word is it or is it a word?) rather than the specific exemplar to which it corresponds (e.g., which specific exemplar is it?). Rarely do we need to recognize an exemplar (e.g., "band" in lowercase 12-point Times font) in word processing tasks or in everyday reading situations, and rarely do cognitive experiments require participants to do so (for an exception, see Burgund & Marsolek, 1997). Also according to this theory, the use of unfamiliar stimuli may alter the situation. Left-hemisphere advantages may not be observed in visual-word processing studies using unfamiliar stimuli because novel visual whole forms can be processed effectively by a specific subsystem, which may counteract any tendency for a left-hemisphere advantage caused by the goals of the experimental task.

Some of the evidence in support of this theory comes from visual-form classification studies. Marsolek (1995) conducted experiments in which subjects first viewed unfamiliar letter-like forms (stick figures) presented in the central visual field and learned to classify these forms into eight different categories. Then, they were asked to classify laterally presented forms into the newly learned categories. Subjects classified the previously unseen central tendencies (prototypes) of the categories more efficiently when they were presented directly to the left hemisphere than when they were presented directly to the right. An abstract subsystem should excel at storing prototypes for categories in particular because prototypes contain the features shared by many members of a category but not features that are distinctive to different exemplars in a category. In addition, subjects classified the forms that were previously presented during the learning phase more efficiently when those forms were presented directly to the right hemisphere than when they were presented directly to the left. A specific subsystem should excel at storing the previously presented exemplars in particular because it differentiates specific exemplars effectively.

These results support the theory that dissociable neural subsystems are involved. In divided-visual-field experiments, when stimuli are presented directly to one hemisphere, subsystems in that hemisphere are given advantages in timing and in the quality of the information received over subsystems in the other hemisphere (as measured via neuronal firing, e.g., Gross, Rocha-Miranda, & Bender, 1972, and amplitudes of functional magnetic resonance signals, Tootell, Mendola, Hadjikhani, Liu, & Dale, 1998, following contralateral vs. ipsilateral visual stimulation). Thus, if the characteristic processing of one hypothesized subsystem (storing prototypes effectively) is observed when subsystems in the left hemisphere are advantaged by the visual input, and if the characteristic processing of another hypothesized subsystem (storing exemplars effectively) is observed when subsystems in the right hemisphere are advantaged by the visual input, then the two subsystems appear to operate at least relatively independently.

Similar results were obtained in another study when familiar stimuli (single letters) were used, but the familiarity of the visual format varied. Bryden and Allard (1976) presented letters printed in ten different fonts to the right or left visual field. Most of the letters were identified more accurately when presented directly to the left hemisphere than to the right, but the letters printed in two of the fonts yielded the opposite result. The two fonts that led to a right-hemisphere advantage differed from the other fonts in being much more script-like and atypical. In other words, a left-hemisphere advantage was observed when letters were presented in prototypical fonts (sans serif), whereas a right-hemisphere advantage was observed when letters were presented in the relatively less familiar or less prototypical of the fonts (serif).

Other evidence more directly indicates that a specific subsystem in the right hemisphere stores novel visual wholes effectively (Marsolek, Schacter, & Nicholas, 1996). In repetition priming experiments, participants first read centrally presented word pairs (one word above the other) and then completed word–stems presented beneath (complete) context words in the left or right visual field. Word–stem completion priming that was specific to a letter-case match between prime words and test stems was found only when the context word was the same word that had previously appeared above the primed completion word and the test items were presented directly to the right hemisphere. Priming that was not letter-case specific did not depend on context or hemisphere of direct stimulus presentation. Thus, a subsystem that stores the visually distinctive information needed to differentiate lowercase and uppercase versions of the same word appears to operate more effectively in the right hemisphere than in the left. Also, letter-case specific priming was dependent on visual context, therefore this specific visual-form subsystem apparently stores word pairs as single novel whole representations.

Most important for present purposes, these results indicate that left-hemisphere advantages have been observed for visual forms that are very typical for their shape categories, such as prototypes or forms that are visually very similar to prototypes (e.g., the letter "a" in a common font). In contrast, left-hemisphere advantages have not been observed (and sometimes right-hemisphere advantages are observed) for visual forms that are very atypical for their shape categories, such as forms that are distinctive or dissimilar to the prototypes (e.g., a letter in an unfamiliar serif font), or when novel visual whole representations are stored. By the abstract and specific subsystems theory, a left-hemisphere advantage may not be observed for processing visually unfamiliar word forms.

A different prediction concerning asymmetries in processing visual words comes from the theory that the left hemisphere contains a visual lexicon that is not present in the right hemisphere (Arguin, Bub, & Bowers, 1998; Bowers, 1996; Jordan et al., 2003; Miozzo & Caramazza, 1998). For example, Jordan et al. (2003) hypothesize that stimuli presented directly to the left hemisphere are advantaged by direct access to lexical representations that allow word recognition. Words presented directly to the right hemisphere are disadvantaged by having to cross commissures to the left hemisphere for recognition to occur. In addition, neuroimaging and neuropsychological results have long suggested that areas in the left hemisphere play very important roles in visual-word recognition (Beauregard et al., 1997; Beversdorf, Ratcliffe, Rhodes, & Reeves, 1997; Damasio & Damasio, 1983; Petersen, Fox, Snyder, & Raichle, 1990; Reuter-Lorenz & Baynes, 1992). By the visual lexicon theory, left-hemisphere advantages should always be observed for visual-word recognition, no matter what kinds of word stimuli are presented.

Recently, Polk and Farah (2002) used functional magnetic resonance imaging to investigate the "visual-word-form area" of the brain. This is an area in the left ventral visual stream that has been activated by words and word-like stimuli in previous studies (Petersen et al., 1990). In the new experiment, subjects passively viewed different types of stimuli including words, pseudowords, and consonant strings as well as alternating-case versions of words and pseudowords. They observed (as Petersen et al. had before) that this area was more activated by words and pseudowords than by consonant strings. More important, no difference in activation was observed between words and pseudowords presented in alternating-case format vs. words and pseudowords presented in pure-case formats. This indicates that the left-hemisphere visual-word-form area is not sensitive to the perceptual familiarity of the stimuli. If this area underlies a visual lexicon that is needed for visual-word processing, then alternating-case words should yield the same kind of left-hemisphere advantage in divided-visual-field experiments that lowercase and uppercase words yield, despite the fact that alternating-case words are visually unfamiliar forms.

Alternating case (or case mixing) has been a very useful method of examining visual-word recognition in behavioral studies (Besner, 1983). Several recent studies have directly measured the effect of case alternation on lateralized word presentations (Fiset & Arguin, 1999; Jordan et al., 2003; Lavidor & Ellis, 2001; Lavidor et al., 2002). First, Jordan et al. have used the word-superiority effect (Reicher, 1969; Wheeler, 1970) to demonstrate that alternating-case words are processed more effectively when presented directly to the left hemisphere than to the right. In that study, a word, a pseudoword, or a consonant string was presented in uppercase, lowercase, or alternating case briefly in the left or right visual field. After the string disappeared, a row of dashes appeared in the center of the screen to correspond with the letters of the flashed word. Above and below one of the dashes, two different letters were presented. The subject then had to decide which of those two letters had been presented in that position in the previous letter string. The typical word-superiority effect was observed, in that participants were more accurate when words were presented than when consonant strings were presented. In addition, this word-superiority effect was greater when strings were presented directly to the left hemisphere than to the right, and this asymmetry effect was observed for alternating-case, uppercase, and lowercase words. This finding supports the left-hemisphere lexicon theory, given that a hallmark of the visual lexicon is that it includes knowledge of how letters can be sequenced to form valid words, and given that top–down processing from word representations to letter representations presumably underlies the word-superiority effect.

However, it is not clear whether the top–down processing underlying the word-superiority effect takes place from *visual* word representations to letter representations. One could argue that top–down processing from *post-visual* word representations (e.g., phonological or semantic word representations) can support the effect, given the highly interactive nature of different processing subsystems of the brain (e.g., for an argument that phonological recoding is involved, see Carr & Pollatsek, 1985). If so, evidence from the Reicher–Wheeler task may not strongly constrain theories of the *visual* processing of word forms in areas of extrastriate visual cortex.

Lexical decision tasks have been used in other studies to examine the effect of alternating case on lateralized word presentations. In these studies, word/nonword decisions were made after letter strings were presented directly to the left or right hemisphere. Fiset and Arguin (1999) reported that case alternation detrimentally affected performance following direct left-hemisphere presentations only. However, from this brief report, it cannot be verified whether a left-hemisphere advantage (over the right) was observed for the alternating-case stimuli. This experiment also lacked an uppercase condition to fully counterbalance the experiment (see Note 1 in Jordan et al., 2003). Other researchers compared uppercase, lowercase, and alternating-case performance in the lexical decision task and reported more complete results (Lavidor & Ellis, 2001; Lavidor et al., 2002). Most important, the typical left-hemisphere advantage was observed for lowercase words (magnitudes of 41 and 39 ms in Experiments 1 and 2, respectively) and for uppercase words (magnitudes of 40 and 44 ms, in Experiments 1 and 2, respectively), but it was unclear whether significant effects extended to alternating-case words (Lavidor et al., 2002). For alternating-case words, a numerical left-hemisphere advantage was found (magnitudes of 12 ms in both Experiments 1 and 2), but the reported results did not allow a test of whether these effects were significant; the researchers were interested in different questions. To the extent that the left-hemisphere advantage for processing alternating-case words may be reliable in this study, the results support the left-hemisphere lexicon theory, in that they indicate that the left-hemisphere advantage for processing words is observed even for unfamiliar visual-word forms (alternating-case words).

However, evidence from the lexical decision task may not be the most useful for testing theories of visual-word processing. Mayall and Humphreys (1996) compared performance with mixed-case words and pure-case words on several word tasks and demonstrated that case mixing had more of a cost on the lexical decision task than on either the word naming or semantic classification tasks. These findings support the idea that a "familiarity discrimination mechanism" may be involved in lexical decision (Besner, 1983). Because alternating case disrupts the outline shape of a word form, this manipulation reduces the familiarity of the overall form. Besner has argued that a crude estimate of this kind of familiarity of the overall form can be used to perform a lexical decision, independently of an identification of which word was presented. If so, the processing in this task may not reflect the processing that takes place when a visual-form input is recognized or identified per se, and results from other tasks are needed to test the main question of whether a left-hemisphere advantage is observed for unfamiliar forms of words (e.g., alternating-case words).

Therefore, in this study, the perceptual identification task was used to assess word recognition performance. In the perceptual identification task, words are presented very briefly, and participants are asked to visually identify and write down each word. Unlike the lexical decision task, this task requires identification of the word, and a crude estimate of familiarity of the overall form would not suffice for accurate performance. In addition, unlike the Reicher–Wheeler task, perceptual identification involves simple recognition of a word, and interpretation of results does not rely on assumptions about the particular representations involved in a top–down process that takes place after identification of the word.

2. Experiment 1

In this experiment, participants perceptually identified visual words presented directly to the left or right hemisphere (briefly in the left or right visual field). The words were lowercase, UPPERCASE, or AlTeRnAtInG-cAsE. The hypotheses were as follows. If the typical left-hemisphere advantage in visual-word processing is observed for uppercase and lowercase words but not for alternating-case words in a significant interaction effect, the abstract/specific subsystems theory would be supported. If, on the other hand, the left-hemisphere advantage is significant for all three stimulus types, then the theory of a left-hemisphere lexicon would be supported.

2.1. Method

2.1.1. Subjects

Sixty undergraduates (30 male and 30 female) at the University of Minnesota participated for course extra credit. All subjects were right-handed as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). The average laterality quotient was 0.86.

2.1.2. Materials

Ninety-six four-letter words were selected using only letters of the alphabet for which the uppercase letter is visually dissimilar from the lowercase letter (a/A, b/B, d/D, e/E, f/F, g/G, h/H, l/L, m/M, n/N, r/R, and t/T; Marsolek, 2004), according to cluster analyses reported in Boles and Clifford (1989). (q/Q is also a dissimilar letter but was not used in any of the four-letter words.) Words composed of these dissimilar-case letters were used to maximize the effect of presenting words in alternating case (e.g., "bAnD" is more visually dissimilar to "band" than "cOwS" is to "cows"). The words were medium frequency (mean frequency of occurrence in written English = 73.2; Francis & Kucera, 1982). The words were presented in three manners: lowercase, uppercase, or alternating-case. For each participant, half of the alternating-case words began with an uppercase letter while the other half began with a lowercase letter. The words were presented in 24-point bold format in five different fonts: Arial, Courier, Helvetica, Times, or Verdana, with font manipulated between subjects.

Six counterbalancing lists of 16 words each were generated, with mean word frequency balanced across lists. For each participant, the six lists were used to represent the six conditions defined by orthogonally combining hemisphere of direct presentation (left vs. right) and word case (lowercase vs. uppercase, vs. alternating-case). Counterbalancing of stimuli was accomplished by rotating lists through those conditions across participants, so that each word was used to represent each experimental condition an equal number of times across participants (including both genders).

Stimuli were presented on a NEC AccuSync 75F monitor controlled by an Apple Power Macintosh 7600/132. Participants placed their head in a chin rest that kept their eyes 50 cm from the monitor.

2.1.3. Procedure

Participants were tested in individually conducted sessions. They were told that they would view words printed in all lowercase, all uppercase, or alternating lowercase and uppercase letters (e.g., "WoRd"). They were told that the words would be presented very briefly to the left or right of the center of the display and that their task was to visually identify the word and write it down on a response sheet as accurately as possible. They did not have to write their word responses in any particular manner (e.g., they did not have to write word responses in the letter-cases used for visual presentation). In addition, the instructions encouraged participants to make a guess if a word was not identified with confidence, and the experimenter emphasized that each stimulus was a genuine word in the English language.

The sequence of events for each trial was as follows. Each trial was initiated by the presentation of a fixation point (a dot) in the center of the display for 500 ms. Participants were instructed to focus their eyes on the dot and to not attempt to guess the side on which the next stimulus would be presented. Once the dot disappeared, a word appeared briefly in the left or right visual field. Each word was centered 2.23 cm (2.55°) to the left or right of the center of the display, with the inner edge of the word never appearing closer than 1 cm (1.15°) from the center of the display. For lowercase and uppercase words, the presentation time was 13 ms, and for alternating-case words, the presentation time was 144 ms. A pilot study determined that 13 ms presentations of lowercase and uppercase words yielded identification performance that avoided ceiling effects in accuracy and 144 ms presentations of alternating-case words yielded identification performance that was similar to the mean performance with lowercase and uppercase words.

Words were presented in a pseudorandom order. The order was constrained so that no more than three consecutive words would be presented to the same visual field and so that no more than three consecutive words would be presented in the same letter case. Twelve additional trials were presented (using 12 additional word stimuli) at the beginning of the session for practice and warm-up.

2.2. Results

In both experiments reported in this article, a response was scored as correct only if the response word matched the presented word exactly. This strict criterion meant that no differences such as plural and past tense forms were accepted. Identification accuracy levels for uppercase, lowercase, and alternating-case words are shown in Fig. 1.

Two repeated-measures analyses of variance (ANOVAs) were conducted, one using participants as the random variable (denoted F_1 below) and the other using items as the random variable (denoted F_2 below). The dependent variable for both analyses was percent accuracy of perceptual identification. Both ANOVAs examined two within-subject variables, hemisphere of direct word presentation (left vs. right) and word case (lowercase vs. uppercase vs. alternating-case). Font of word stimuli and gender of participant were included in initial analyses, but did not exhibit any significant effects and so were not included in the analyses reported below.

The most important result was that the interaction between hemisphere of direct word presentation and word case was significant, $F_1(2,118)=27.15$, $MS_e=117.67$, $p<.0001$, $F_2(2,190)=19.16$, $MS_e=266.73$, $p<.0001$. Simple effect contrasts indicated a strong left-hemisphere advantage for the uppercase words (left = 84.4%, right = 68.0%), $F_1(1,177)=58.02$, $MS_e=138.3$, $p<.0001$, $F_2(1,285)=37.24$, $MS_e=344.8$, $p<.0001$ and lowercase

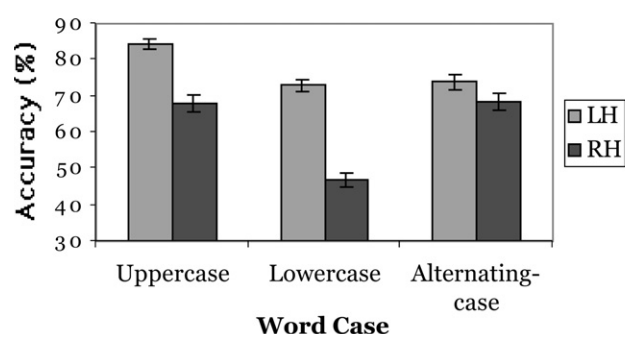

Fig. 1. Results from Experiment 1. Perceptual identification accuracy is plotted as a function of word case (uppercase, lowercase, and alternating-case) and hemisphere of direct test presentation (LH, left hemisphere or RH, right hemisphere).

words (left = 72.9%, right = 46.9%), $F_1(1,177) = 147.1$, $MS_e = 138.3$, $p < .0001$, $F_2(1,285) = 94.41$, $MS_e = 344.8$, $p < .0001$. A simple effect contrast also indicated a left-hemisphere advantage for alternating-case words (left = 73.9%, right = 68.4%), $F_1(1,177) = 6.36$, $MS_e = 138.31$, $p < .05$, $F_2(1,285) = 4.08$, $MS_e = 344.8$, $p < .05$, but this left-hemisphere advantage was significantly smaller in size (5.4%) than the left-hemisphere advantages observed for uppercase words (16.4%) and lowercase words (26.0%), $F_1(1,118) = 42.32$, $MS_e = 117.67$, $p < .0001$, $F_2(1,190) = 29.88$, $MS_e = 266.73$, $p < .0001$, for the interaction contrasts.

The other significant effects were the following. Accuracy was higher when words were presented directly to the left hemisphere (77.0%) than to the right hemisphere (61.1%) in a main effect of hemisphere of direct word presentation, $F_1(1,59) = 127.28$, $MS_e = 179.61$, $p < .0001$, $F_2(1,95) = 152.58$, $MS_e = 239.72$, $p < .0001$. Accuracy differed for uppercase words (76.1%), alternating-case words (71.1%), and lowercase words (59.9%), in a main effect of word case, $F_1(2,118) = 38.30$, $MS_e = 218.20$, $p < .0001$, $F_2(2,190) = 27.67$, $MS_e = 483.29$, $p < .0001$. Accuracy was higher for the uppercase words (76.2%) than for lowercase words (59.9%), according to simple effect contrasts, $F_1(1,118) = 73.07$, $MS_e = 218.2$, $p < .0001$, $F_2(1,190) = 52.79$, $MS_e = 483.29$, $p < .0001$, which will be discussed below.

2.3. Discussion

The main result from this perceptual identification experiment was that the typical left-hemisphere advantage in processing visual words was observed to be strong for uppercase words and lowercase words, but was weaker for alternating-case words. A strong interaction effect and an interaction contrast effect indicated that the left-hemisphere advantages for processing uppercase and lowercase words are greater than the left-hemisphere advantage for processing alternating-case words. Unfortunately, this result is somewhat equivocal for testing the main question of this study, because the significant left-hemisphere advantage in processing alternating-case words supports one theory, but the finding that this left-hemisphere advantage is significantly smaller than those for uppercase and lowercase words supports the alternative theory. For this reason, another tack was taken in Experiment 2 to investigate the main question.

In alternating-case words, the form as a whole is unfamiliar, but the individual letters are still in a familiar format. Stimuli that are unfamiliar at both the word and letter levels may provide a stronger test of the hypothesis that a left-hemisphere advantage will not be observed for unfamiliar word form stimuli. Thus, for Experiment 2, a new font was created. Ten individual exemplars of each letter (lowercase and uppercase versions in five different fonts) were first size-normalized into a common grid and then the overlap of the ten exemplars was determined on a pixel-by-pixel basis. The number of exemplars that overlapped in a particular pixel determined the gray level of that pixel. Thus, by finding the degree of overlap of these exemplars over all pixels in the grid, the central tendency, or prototype, of each letter was obtained. These prototype letters were used to form words that, like alternating-case words, still retain the same phonological and semantic information as normally presented words, but are visually unfamiliar at both the word *and* letter levels (see Fig. 2). Because any "prototype font" word was based on ten familiar exemplars, recognition was still possible even though the words were presented in an entirely unfamiliar format.

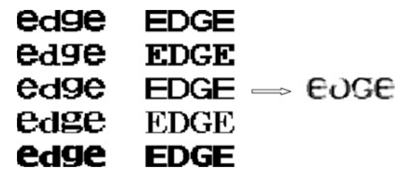

Fig. 2. Examples of the size and aspect-ratio normalized words used in Experiment 2. The two columns show lowercase and uppercase versions of the word "edge" in the five fonts used (Arial, Courier, Helvetica, Times, and Verdana). These 10 exemplars were used to create the prototype-font version depicted on the right.

3. Experiment 2

As in Experiment 1, participants perceptually identified visual words presented directly to the left or right hemisphere (briefly in the left or right visual field). The words were lowercase, uppercase, or prototype-font words. The hypotheses were as follows. If the typical left-hemisphere advantage in visual-word processing is observed for uppercase and lowercase words, but not for prototype-font words, the abstract/specific subsystems theory would be supported. However, if the left-hemisphere advantage is significant for all three stimulus types, then the theory of a left-hemisphere lexicon would be supported.

3.1. Method

3.1.1. Subjects

Sixty undergraduates (30 male and 30 female) at the University of Minnesota participated for course extra credit. All subjects were right-handed as measured by the Edinburgh Handedness Inventory (Oldfield, 1971). The average laterality quotient was 0.85.

3.1.2. Materials

The same words were used as in Experiment 1. The words were presented in three manners: lowercase, uppercase, or in a prototype font. For all three formats, individual letters were fit into a 24 by 24 matrix so that the common pixel information could be determined. This forced each letter to be on the same size and aspect-ratio scale, and it caused ascenders and descenders to be presented in line with other letters. The prototype font was composed of lowercase and uppercase letters in five different fonts, Arial, Courier, Helvetica, Times, and Verdana, which were the same (relatively frequently encountered) fonts used in Experiment 1. Ten matrices were created for each letter (uppercase and lowercase in each of the five fonts). The common visual information that five or more of these different matrices shared was preserved and used to create a prototype version of a letter. Pixels common to all ten matrices were printed in black, and lighter grayscales were used for fewer matches (down to five). Words in all three formats (lowercase, uppercase, and prototype font) were formed by sequencing letters with a one-pixel space between each letter. Examples of the three word formats are shown in Fig. 2.

3.1.3. Procedure

The procedure was the same as in Experiment 1, with the following exceptions. First, participants were told that some of the words would appear slightly distorted. Second, for lowercase and uppercase words, the presentation time was 13 ms, and for prototype-font words, the presentation time was 183 ms. The ratio of presentation times, 13/183, was very similar to the ratio of the average number of pixels activated for lowercase/uppercase words vs. prototype-font words. Also, a pilot study indicated that accuracy rates for prototype-font words would be relatively low when they were presented for 183 ms, but the 183-ms presentation time was the longest that could be used while assuring that attention-based saccades could not be made to the targets before they disappeared from the monitor.

3.2. Results

Responses were scored using the same strict criterion used in Experiment 1. Identification accuracy levels for uppercase, lowercase, and prototype-font words are shown in Fig. 3.

Two repeated-measures analyses of variance were conducted, one using participants as the random variable (denoted F_1 below) and the other using items as the random variable (denoted F_2 below). The dependent variable for both analyses was percent accuracy of perceptual identification. The by-subjects ANOVA examined two within-subject variables, hemisphere of direct word presentation (left vs. right) and word format (lowercase vs. uppercase vs. prototype-font), and one between-subjects variable, font (Arial vs. Courier vs. Helvetica vs. Times vs. Verdana). Gender was included

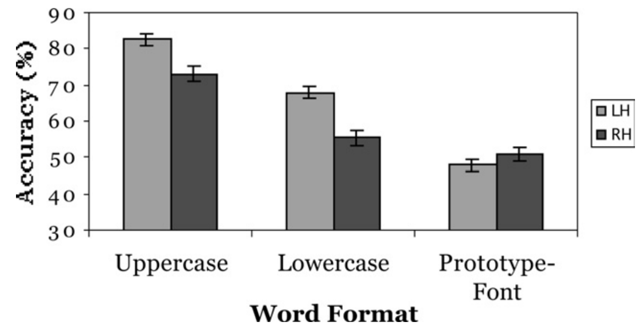

Fig. 3. Results from Experiment 2. Perceptual identification accuracy is plotted as a function of word format (uppercase, lowercase, or prototype font) and hemisphere of direct test presentations (LH, left hemisphere or RH, right hemisphere).

in an initial by-subjects analysis, but it did not exhibit any significant effects and so was not included in the analysis reported below. The by-items ANOVA examined only the two within-subjects variables.

The most important finding was a significant interaction between hemisphere of direct word presentation and word format, $F_1(2,110)=22.44$, $MS_e=907.1$, $p<.0001$, $F_2(2,190)=15.52$, $MS_e=195.2$, $p<.0001$. Simple effect contrasts indicated a strong left-hemisphere advantage for the uppercase words (left = 82.9%, right = 73.3%), $F_1(1,220)=24.47$, $MS_e=114.2$, $p<.001$, $F_2(1,285)=21.28$, $MS_e=210.1$, $p<.0001$ and lowercase words (left = 68.1%, right = 55.6%), $F_1(1,220)=40.8$, $MS_e=114.2$, $p<.0001$, $F_2(1,285)=34.06$, $MS_e=210.1$, $p<.0001$, but no significant hemisphere difference for prototype-font words (left = 48.1%, right = 51.1%), $F_1(1,220)=2.37$, $MS_e=114.2$, $p>.12$, $F_2(1,285)=1.60$, $MS_e=210.1$, $p>.20$. In fact, the numerical trend was in the direction of a right-hemisphere advantage.

The other significant effects were the following. Accuracy was higher when words were presented directly to the left hemisphere (66.5%) than to the right hemisphere (59.9%) in a main effect of hemisphere of direct word presentation, $F_1(1,55)=19.21$, $MS_e=189.8$, $p<.0001$, $F_2(1,95)=24.66$, $MS_e=239.8$, $p<.0001$. Accuracy differed for uppercase words (78.1%), lowercase words (61.8%), and prototype-font words (49.6%) in a main effect of word case, $F_1(2,110)=178.54$, $MS_e=137.6$, $p<.0001$, $F_2(2,190)=29.26$, $MS_e=1369.0$, $p<.0001$. Simple effect contrasts indicated that accuracy was higher for the uppercase words (78.1%) than for lowercase words (62.0%), $F_1(1,110)=115.23$, $MS_e=137.6$, $p<.0001$, $F_2(1,190)=18.81$, $MS_e=1369.0$, $p<.0001$, which will be discussed below. Finally, a significant interaction was observed between word format and font, $F_1(2,8)=4.64$, $MS_e=137.6$, $p<.001$. Simple effect contrasts indicated no difference in accuracy between uppercase (62.7%) and lowercase (63.8%) words in the Courier font, $F_1<1$, but differences between those conditions with Arial font (84.1% vs. 60.2%), $F_1(1,165)=30.02$,

$MS_e = 229.3$, $p < .001$, Helvetica font (82.4% vs. 68.4%), $F_1(1, 165) = 10.34$, $MS_e = 229.3$, $p < .001$, Times font (78.6% vs. 60.6%), $F_1(1, 165) = 16.95$, $MS_e = 229.3$, $p < .001$, and Verdana font (82.0% vs. 57.3%), $F_1(1, 165) = 30.70$, $MS_e = 229.3$, $p < .001$. The Courier font is the only one of the five fonts that is proportional (normally presented with all letters in the same size). Thus, the results indicate that the lowercase and uppercase versions of Courier font were identified equally well when they are size normalized, but the lowercase and uppercase versions of the other five fonts were identified differently when size normalized. The effect was not predicted, and no explanation is readily apparent.

3.3. Discussion

The most important result from this experiment was that the typical left-hemisphere advantage in processing visual words was observed to be strong for uppercase words and lowercase words, but was not observed for prototype-font words (in fact, the numerical trend was in the direction of a right-hemisphere advantage). Prototype-font words were visually unfamiliar, yet readable, thus the finding supports the abstract/specific subsystems theory to a greater degree than the left-hemisphere lexicon theory.

4. General discussion

The goal of this study was to explore boundary conditions for an important general finding in the neuropsychology of reading. First, the results from Experiment 1 indicated that the typical left-hemisphere advantage in visual-word processing was weak for alternating-case words. More important, the results from Experiment 2 indicated an elimination (and numerical reversal) of the ubiquitous left-hemisphere advantage in visual-word processing when unfamiliar word forms were presented. These findings support the prediction from the abstract/specific subsystems theory that the left-hemisphere advantage should be eliminated for visually distinctive and unfamiliar stimuli.

It is worth noting that one aspect of the present results may seem puzzling at first. The lack of a left-hemisphere advantage for processing prototype-font words may seem to contradict the left-hemisphere advantage observed previously for categorizing prototype stick figures (Marsolek, 1995). Several differences between studies may be important, such as (a) the use of pre-experimentally familiar vs. novel visual-form categories (word forms vs. stick figures), (b) the amount of learning or training of the relevant categories (years vs. less than a half hour), and (c) a relatively small vs. relatively large amount of visual information per prototype (prototype-font words contained fewer pixels than their lowercase or uppercase counterparts, whereas the prototype stick figures contained about the same number of pixels as the exemplars in their categories). Any of these differences, or some combination, may be responsible for the different patterns of results. Perhaps the most important point for present purposes is that the prototype-font words used in the present experiment appeared visually unfamiliar to participants (see Fig. 2). Indeed, the prototype-font words were identified less accurately than the lowercase or uppercase words (see Fig. 3). In contrast, the prototype stick figures used by Marsolek appeared visually familiar to the participants, as though they were among the figures that were viewed during initial training. Indeed, in two of the three experiments, the (previously unseen) stick-figure prototypes were categorized more efficiently than the exemplars that had been viewed during training.

A very interesting and initially unexpected finding in both Experiments 1 and 2 was the greater perceptual identification performance for uppercase words than for lowercase words in both direct left- and right-hemisphere presentations. Previous studies have demonstrated the opposite effect—a lowercase advantage over uppercase in visual-word processing. This lowercase advantage has been observed in studies using central presentations (Mayall & Humphreys, 1996) as well as in studies using lateralized presentations (Jordan et al., 2003; Lavidor & Ellis, 2001; Lavidor et al., 2002). Why was an uppercase advantage observed in the present study, but a lowercase advantage observed in the previous studies?

An important difference may be that the previous studies used the lexical decision task (Lavidor & Ellis, 2001; Lavidor et al., 2002; Mayall & Humphreys, 1996) or the Reicher–Wheeler task (Jordan et al., 2003), and the present study used perceptual identification. Given that lowercase words are more frequently encountered in written text than uppercase words, the kind of crude estimate of overall form familiarity hypothesized to be assessed in a familiarity discrimination mechanism (Besner, 1983) should be higher for lowercase words than for uppercase words. This could underlie the lowercase advantage observed in lexical decision tasks. Conversely, because uppercase words are less frequently encountered than lowercase words, perceptual identification could be advantaged by uppercase words if they are more visually distinctive than lowercase words.

Alternatively, other differences between lowercase and uppercase words may be important. Visual shape differences that are consistent between lowercase words and uppercase words include that lowercase words tend to (a) be smaller than uppercase words, (b) have more curved parts than uppercase words, and (c) possess shape information in ascenders and descenders that is not shared with uppercase words, etc. Any of these differences, or some combination, could play a role in causing uppercase advantages when the task is perceptual identification and lowercase advantages when the task is lexical decision.

The uppercase advantage in this study plays a role in a characterization of the results from Experiment 1 that emphasizes comparisons between the stimulus conditions within each hemisphere presentation condition, rather than comparisons between hemisphere presentation conditions within the stimulus conditions. We suggest above that uppercase words were identified more accurately than lowercase words overall because they are less frequently encountered and hence more visually distinctive. We also suggest above that words were identified more accurately when presented directly to the left hemisphere than to the right overall because the nature of the task was to identify the word and not the word-form exemplar that was presented, which advantages an abstract subsystem. This may explain the pattern of results obtained in those four conditions (see Fig. 1). In this context, one could account for the results from alternating-case words in the following manner. Without additional factors, identification rates for alternating-case words may be expected to lie between those for uppercase words and lowercase words, in both of the hemisphere presentation conditions. However, when words are presented directly to the left hemisphere, the novelty of the overall word form in alternating-case words may produce a cost in processing in an abstract subsystem that reduces identification rates to the lower level of lowercase words. And when words are presented directly to the right hemisphere, the novelty of the overall word form in alternating-case words may produce a benefit in processing in a specific subsystem that enhances identification rates to the higher level of uppercase words.

As described in Section 1, in a neuroimaging study, Polk and Farah (2002) found no significant activation differences between pure-case and alternating-case words in the left visual-word-form area. At first glance, this may seem to contradict our observation in Experiment 1 that uppercase words were identified more accurately than alternating-case and lowercase words when presented directly to the left hemisphere. However, using a blocked design, Polk and Farah presented both uppercase and lowercase words in the same "pure-case" scanning blocks, thus they were not able to separate activation from processing uppercase vs. lowercase words and compare each against processing of alternating-case words. In fact, we analyzed our results with Helvetica font words (most comparable to the Geneva font words used by Polk and Farah) from Experiment 1 in a similar way, by combining results from uppercase and lowercase trials to produce a pure-case condition and comparing them against results from the alternating-case condition. No significant difference ($p > .30$) was found between identification of pure-case and identification of alternating-case words presented directly to the left hemisphere in this analysis.

In Experiment 2, we generated prototype-font words to serve as very unfamiliar, yet recognizable, visual-word forms. This stimulus manipulation may have involved a manipulation of the spatial frequency content of the stimuli in addition to a manipulation of the familiarity, because the prototype-font words are similar to what would be produced by a low-pass blurring of the pure-case stimuli (see Fig. 2). This is interesting because right-hemisphere advantages have been observed for identification and discrimination of low spatial-frequency information (e.g., Christman, Kitterle, & Hellige, 1991; Kitterle, Christman, & Hellige, 1990; Kitterle & Selig, 1991). It is also consistent with our theory. Our theory is that a specific subsystem in the right hemisphere processes whole-based information effectively in order to accomplish specific exemplar recognition. We have hypothesized that the whole-based nature of the processing in this subsystem (accomplished through relatively distributed representations) is what is responsible both for processing unfamiliar forms effectively (the novelty of an unfamiliar form is in its whole-based structure, not in its parts) and for processing low spatial-frequency information effectively (low spatial-frequency information can be reflected effectively by integrated whole representations that do not have independent part representations; see Marsolek & Burgund, 1997).

On a related point, one aspect of the present results suggests that the unfamiliarity of the prototype-font words may be more important than the low spatial-frequency content of those words in predicting the numerical right-hemisphere advantage observed in Experiment 2. An important piece of evidence supporting right-hemisphere advantages in processing low spatial-frequency information is that increases in stimulus exposure duration selectively benefits processing following left hemisphere presentations (see Christman, 1989). However, in Experiment 2, to attempt to equalize levels of performance for different stimuli, prototype-font words were exposed for longer durations than pure-case words, and yet a reversal of the typical left-hemisphere advantage in visual-word recognition was observed for the prototype-font words.

In closing, it is worth noting that a relatively simple explanation for the left-hemisphere advantage in visual-word processing relates to the importance of initial letters to word recognition. Words presented in the right visual field have the initial letters appear closer to the central fixation point than words presented in the left visual field, which could result in greater visual acuity for the important initial letters and hence a left-hemisphere advantage. Thus, another important aspect of the present results is that the ubiquitous left-hemisphere advantage was eliminated or reversed even with standard horizontal presentations, apparently because the word forms were unfamiliar. Other researchers have used vertical presentations of words in divided-visual-field experiments to avoid the problem of differential acuity for parts of words. However, given that the vast majority of reading experiences in everyday life involves horizontal words, the word form representations of interest in the present study are carved and maintained by processing horizontal words. We would argue that experiments with vertical presentations do not measure the processes that normally occur in word recognition (and instead likely reflect less typical sequential or letter-by-letter reading processing) as effectively as experiments with horizontal presentations.

In sum, the ubiquitous left-hemisphere advantage in processing visual words has a limit, one that appears to involve the familiarity of the visual forms that are processed. Further exploration of this kind of boundary condition should help to uncover important aspects of the neuropsychology of word recognition and reading.

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