A multistream model of visual word recognition

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Four experiments are reported that test a multistream model of visual word recognition, which associates letter-level and word-level processing channels with three known visual processing streams isolated in macaque monkeys: the magno-dominated (MD) stream, the interblob-dominated (ID) stream, and the blob-dominated (BD) stream (Van Essen & Anderson, 1995). We show that mixing the color of adjacent letters of words does not result in facilitation of response times or error rates when the spatial-frequency pattern of a whole word is familiar. However, facilitation does occur when the spatial-frequency pattern of a whole word is not familiar. This pattern of results is not due to different luminance levels across the different-colored stimuli and the background because isoluminant displays were used. Also, the mixed-case, mixed-hue facilitation occurred when different display distances were used (Experiments 2 and 3), so this suggests that image normalization can adjust independently of object size differences. Finally, we show that this effect persists in both spaced and unspaced conditions (Experiment 4)—suggesting that inappropriate letter grouping by hue cannot account for these results. These data support a model of visual word recognition in which lower spatial frequencies are processed first in the more rapid MD stream. The slower ID and BD streams may process some lower spatial frequency information in addition to processing higher spatial frequency information, but these channels tend to lose the processing race to recognition unless the letter string is unfamiliar to the MD stream—as with mixed-case presentation.

Since the beginning of experimental psychology, researchers have been interested in how humans recognize words during reading. For example, Cattell (1886) hypothesized that words were processed analytically, as component letters, whereas Pillsbury (1897) hypothesized that words were processed holistically, as whole units. Investigators have inferred from the results of many studies that both types of processing are involved (e.g., Rayner & Pollatsek, 1989). However, few contemporary models of word recognition are based on the physiology of the visual system.

The experiments in this article were motivated by a hybrid model that is an integration of a physiology-based model of the visual system with an information-processing model; we call this the *multistream model*. This model contains a lexicon, the activation of which plays a central role in decisions about whether letter strings are words. However, it differs from most other

models of visual word recognition in two important ways: The processing streams of the multistream model analyze spatial frequency information, not visual features; and the different processing channels of the multistream model are responsive to different aspects of the stimulus. That is, letters are not formed from features, and words are not necessarily formed from component letters. Instead, words and letters are formed separately through the use of spatial frequency analysis of different “grain sizes” (i.e., words are recognized from lower spatial frequencies, and letters are recognized from higher spatial frequencies). We elaborate on each of these differences and then describe four experiments in which we tested predictions of the multistream model.

Spatial Frequency Filters Versus Features

Although many researchers have assumed that perceptual objects (e.g., words) are perceived as collec-

tions of features (e.g., Adams, 1979; Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; McClelland & Rumelhart, 1981), two classes of evidence recommend serious consideration of recognition models based on spatial frequency. First, Gervais, Harvey, and Roberts (1984) showed that letter confusions are better predicted by a spatial-frequency model than by a feature model. (We are unaware of any comparisons of a spatial-frequency model with a feature model for whole words.) Second, there is considerable evidence that at least at the retinal and lateral geniculate nucleus (LGN) levels, the visual system uses spatial-frequency filtering rather than features to process visual information (e.g., De Valois & De Valois, 1990; Van Essen, Anderson, & Felleman, 1992).

Allen and Emerson (1991; see also Allen, Wallace, & Weber, 1995) proposed a model of word recognition that assumes that the basic units of visual analysis are the spatial-frequency patterns of whole words and their component letters, respectively. This model is the information-processing approach that we integrate into the multistream model.

Cortical Processing Streams in the Primate Brain

Investigating visual information processing in the macaque, Van Essen and his colleagues have distinguished three cortical processing streams—the magno-dominated (MD) stream, the blob-dominated (BD) stream, and the interblob-dominated (ID) stream (Van Essen & Anderson, 1995; Van Essen & DeYoe, 1995). (The BD and ID streams are, collectively, the parvocellular streams.) Recent brain-mapping research suggests that the visual cortex of macaques is quite similar to that of humans—particularly in area V1, the origin of these three processing streams (Orban, Van Essen, & Vanduffel, 2004).

At least two of these three pathways have been studied using physiological (Van Essen & Anderson, 1995; Van Essen et al., 1992; see also Skottun, 2000, 2001), psychophysiological (Lehmkuhle, Garzia, Turner, Hash, & Baro, 1993), and brain imaging (Madden et al., 1996; Petersen, Fox, Snyder, & Raichle, 1990) methods. These studies converge on the following conclusions concerning the characteristic sensitivities of these channels. The MD stream is particularly sensitive to low-spatial-frequency stimuli—0.5 to 1.5 cpd of visual angle (see Legge, Pelli, Rubin, & Schleske, 1985; Merigan, Byrne, & Maunsell, 1991; Skottun, 2000)—has a fast conduction rate and responds to luminance differences but is not sensitive to hue

differences. The BD stream is sensitive to higher spatial-frequency stimuli (>2 cpd; Legge et al., 1985; Skottun, 2000); has a slow conduction rate; is sensitive to hue, particularly to color contrasts (i.e., to variability in hue within a stimulus); and processes certain brightness, texture, and shape information (Livingstone & Hubel, 1987; Van Essen & Anderson, 1995). The ID stream is sensitive to higher spatial-frequency stimuli (again, >2 cpd); has a slow conduction rate; and although responsive to hue variability, is less so than the BD stream (Van Essen & Anderson, 1995). This pathway, too, has been hypothesized to process color, texture, and pattern information (Livingstone & Hubel, 1987). Table 1 summarizes the processing characteristics of these three streams.

There appears to be considerable overlap in the spatial frequency sensitivity of the magnocellular and parvocellular pathways in the low- to mid-spatial-frequency range (e.g., 1.5–3.5 cpd) (Merigan & Maunsell, 1993). The key difference between the pathways, then, appears to be conduction rate; the magnocellular pathway has a faster conduction rate than does the parvocellular pathway (Van Essen & Anderson, 1995).

Peterzell and Teller (2000) examined correlations between contrast sensitivity thresholds across seven levels of spatial frequency (0.27–2.16 cpd of visual angle) of gratings that were yellow–black (i.e., monochromatic or luminance modulated) and seven levels of spatial frequency of gratings that were red–green (i.e., chromatic modulated). Using principal components analysis with a varimax rotation on the 14 threshold variables, Peterzell and Teller interpreted three principal components as representing a lower spatial-frequency monochrome channel, a higher spatial-frequency monochrome channel, and a chromatic channel (see also Dobkins, Gunther, & Peterzell, 2000). These channels plausibly correspond to the MD, ID, and BD channels, respectively, of the model of visual processing of Van Essen and Anderson (1995).

Bar (2004) has presented a two-channel model of object and scene processing that has many similarities to the present approach. In this model, there is a fast, low-spatial-frequency channel (involving the magnocellular pathway) that activates global objects and context, and a slower, higher spatial-frequency channel (probably involving the parvocellular pathway) that carries fine-detailed information. In many object-identification situations, the faster global (blurry) channel can be used; a “candidate set” of similar perceptual objects is activated, and the selection that results in recognition is made by

Table 1
Characteristics of the Magno-Dominated, Interblob-Dominated, and Blob-Dominated Processing Streams

Characteristic	Processing Stream		
	Magnocellular, Magno-Dominated	Parvocellular	
		Interblob-Dominated	Blob-Dominated
Spatial frequency sensitivity	low frequencies	high frequencies	high frequencies
Sensitivity to hue variation	no	no	yes
Temporal frequency sensitivity (movement)	high	low	low
Conduction rate	fast	slow	slow

a top-down contextual module (see Bar, 2004). However, if the global channel cannot recognize an object, detailed information is used by the slower channel. Bar provides magnetoencephalography evidence that suggests that magnocellular activation occurs earlier (at approximately 130 msec after stimulus presentation) than parvocellular activation in object recognition (Bar et al., 2006; Kveraga, Boshyan, & Bar, 2007). Furthermore, Li, VanRullen, Koch, and Perona (2002) provided evidence that humans can recognize highly familiar global objects (e.g., pictures of animals) in the near absence of attention, but that this is not the case when individual letters or other smaller units are used. The data of Bar and Li et al. together encourage the idea that a model employing a low-spatial-frequency, global channel and a higher spatial-frequency, analytic channel might be applied to visual word recognition.

The Multistream Model

The hybrid model of visual word recognition (Allen & Emerson, 1991; Allen & Madden, 1990; Allen, Madden, Weber, & Groth, 1993; Allen et al., 1995; see also Jordan, 1990, 1995; Jordan & Bevan, 1994, 1996; Jordan, Thomas, Patching, & Scott-Brown, 2003) postulates a race to a central processor between information in a whole-word channel and that in a component-letter channel; each pathway attempts to use the spatial-frequency pattern of its basic unit of analysis to form a word code, and word recognition is based on information delivered by the channel that wins the race.

There is a natural compatibility among our hybrid model, the two-channel model of Bar (2004), and the Van Essen et al. (1992) three-stream model of cortical pathways; the integrated multistream model is shown in Figure 1. Specifically, the whole-word channel corresponds plausibly to the MD stream, and the component-letter channel corresponds plausibly to the ID and BD streams. In this mapping, the faster MD stream utilizes lower spatial-frequency information. The ID and BD streams utilize higher spatial-frequency information, with the BD stream being particularly sensitive to hue contrasts. Because the processing rates of the BD and ID streams are slower than that of the MD stream, they form word codes more slowly, so information carried by the MD stream typically wins the processing race.

Various data support this hypothesis. Kelly (1979), for example, who investigated the stabilized contrast-sensitivity function, found that low-spatial-frequency components (in the magnocellular range) were available before high-spatial-frequency components (in the parvocellular range). Legge et al. (1985) found that the critical spatial-frequency bandwidth for reading was 2 cycles per character and that asymptotic reading rates were achieved with characters of between 0.3° and 2°, so that processing was optimal with text in the range of 1–6.67 cpd. This is in the range of sensitivity of all three streams, but evidence that reading speed increases with blurred text relative to high-contrast text (O'Brien, Mansfield, & Legge, 2000) suggests that the MD stream is faster at reading than are the ID and BD streams.

Figure 1. Processing dynamics of the multistream model at three different anatomical levels in the primary visual pathway: A = retinal level, B = lateral geniculate nucleus (LGN) level, and C = V1 (primary visual cortex) level. The transient pathway (T) from the retinae projects primarily to the magnocellular pathway in the LGN. The sustained pathway (S) from the retinae projects primarily to the parvocellular pathway in the LGN. The overlapping of the magnocellular and parvocellular pathways at Level B illustrates that some sustained pathway projections from the retinal level project to the magnocellular LGN layers, even though the vast majority project to the parvocellular layers of the LGN. Likewise, some transient pathway projections from the retinal level project to the parvocellular LGN layers, even though the vast majority project to the magnocellular layers of the LGN. A linkage between brain and psychological levels of representation is illustrated at Level C. Partial LGN activation cascading up to the V1 level is illustrated by dashed lines, and lateral inhibition at the V1 level is illustrated by dashed lines between MD and ID/BD. Note that lateral inhibition is assumed to occur only between streams with different LGN pathways (i.e., MD vs. ID or BD, or vice versa, but not ID vs. BD).

OVERVIEW OF EXPERIMENTS

We report four lexical decision experiments in which we tested predictions of this multistream approach to visual word recognition. The predictions of the multistream model concerned the relative speeds with which experimental participants decide whether letter strings that vary in their composition by color, case, and spacing are words. The predictions were based on assumptions about which of the visual streams carry specific sorts of information and the speeds at which those streams operate. In Experiment 1,

Table 2
Processing Dynamics for the Present Multistream
Model (in Milliseconds)

	Magno-Dominated (Lowercase)	Interblob-Dominated (Mixed Case)	Blob-Dominated (Just Mixed Case, Mixed Hue)	Faster Output (Statistical Facilitation)
Trial 1	400	500	550	500
Trial 2	400	550	500	500
Trial 3	400	500	550	500
Trial 4	400	550	500	500
Mean RT	400	525	525	500

Note—This illustration of parallel independent statistical facilitation is taken from Raab (1962). Example channel processing times are shown for four trials of each of three word stimulus types—lowercase (the MD channel wins); mixed-case, mixed-hue presentation (both ID and BD streams output a code); and mixed-case monochrome presentation (just the ID stream is hypothesized to output a code). If the whole-word stimulus is familiar (e.g., consistent lowercase), the MD stream will typically be used to recognize words rapidly (400 msec). However, if the letter string is presented in mixed case, this would result in an unfamiliar spatial-frequency pattern for the MD stream, but would show familiar patterns for the ID and BD streams, assuming there is a hue contrast necessary for activating the BD stream. When both ID and BD streams output a code and the MD stream is not able to output a code (e.g., mixed-case, mixed-hue presentation), it is assumed that a word will be recognized more rapidly (500 msec) than if just the single ID stream is able to output a code (e.g., for mixed-case monochrome presentation) (525 msec). This advantage of having two parallel, independent, input channels with similar output times operational (both ID and BD), relative to having a single input channel operational (ID), provides the theoretical mechanism for predictions made by the multistream model.

we tested the basic model by comparing case type and hue type across words and nonwords. In Experiments 2 and 3, we used a longer stimulus exposure duration (400 msec instead of 100 msec) and also varied viewing distance (40 cm in Experiment 2 and 60 cm in Experiment 3) in order to determine whether normalization would occur. Finally, in Experiment 4, we replicated Experiment 3, with the added variable of space type (no spaces, spaces).

The stimulus strings used in these experiments were either words or nonwords; in every experiment, participants were instructed to carry out a lexical decision task. For all four experiments, two stimulus characteristics other than stimulus type (i.e., word, nonword) were manipulated—whether the cases of letters in a stimulus string were all the same or mixed (lowercase and uppercase), and whether the hues of the letters in a stimulus string were all the same (i.e., all red, all green) or mixed (both red and green, intermixed). Within experiments, processing efficiency was compared for strings of the four types yielded by crossing two levels of case consistency with two levels of color consistency. In Experiment 4, we also manipulated spacing: Half of the letter strings were presented with no spaces between letters (e.g., “datum”), and the other half were presented with one space between adjacent letters (e.g., “d a t u m”).

We derived two general predictions about visual word recognition from the multistream model. First, we assumed that for same-case words, recognition depends predominantly on information carried by the fast MD stream, whereas for mixed-case strings, recognition depends on information carried by the slower BD and ID streams. From this we predicted that responses to same-case words would be faster or more accurate than those to mixed-case words. Note that this is a common finding in visual word recognition experiments, but one that has been difficult to explain

(e.g., Allen et al., 1993; Allen et al., 1995; Carr & Polatsek, 1985; Coltheart & Freeman, 1974; Mayall, Humphreys, & Olson, 1997). Second, we assumed that mixed-case monochrome strings activate primarily the ID stream that is sensitive to fine detail, but not the BD stream that is sensitive to hue variability, whereas mixed-case, mixed-hue strings activate both the ID stream and the BD stream. Taking these assumptions together with the assumption that the BD and ID streams operate at similar rates, we predicted that responses to mixed-case, mixed-hue strings should, on average, be faster than responses to mixed-case monochrome strings. For the former, recognition would depend on information carried by the faster of the BD and ID streams. Raab (1962) termed this outcome *statistical facilitation*, in which, when two input channels have similar output times (so that Channel A outputs its code to an output buffer before Channel B outputs its code to an output buffer on some trials, but the opposite occurs on other trials), overall word recognition will be faster when working memory selects the faster of the two (see Table 2).

GENERAL METHOD

Participants

Participants were University of Akron undergraduates who participated for research credit. All participants were native speakers of English, reported normal or corrected-to-normal vision, and were screened for red–green color blindness.

Stimulus Materials

For all experiments, two lists of 384 items, each consisting of 192 words and 192 nonwords, were used. Each set of 192 words included 24 from each of the eight classes that result from crossing four levels of word frequency with two levels of length. The four word-frequency categories, defined by number of occurrences per million in the Kučera and Francis (1967) norms, were very high

(255–1,702 occurrences per million), medium-high (141–224 occurrences per million), low (40–52 occurrences per million), and very low (1–5 occurrences per million). The two levels of length were five and six letters. From each word, a corresponding nonword was generated by transforming one letter. For example, one five-letter low-frequency word was “loose”; its corresponding nonword was “loost.” We attempted to form nonwords that were orthographically correct, and this was the case for most stimuli. All of these items are presented in the Appendix.

In all of the present experiments, the stimuli were assigned equally often to each of the four conditions. To accomplish this, we divided two sets of 192 words into four groups, each of which contained 6 items from each word frequency $\times$ word length class; the 192 nonwords from the complementary set were similarly divided into groups. For each set of words, the four groups (of 48 words and 48 nonwords) were balanced over the four conditions, so that approximately 25% of the participants experienced each word group in each experimental condition.

In lowercase strings, all letters were lowercase. In monochrome strings, all letters were either red or green. In mixed-case monochrome strings, in which all letters were either all red or all green, lowercase was assigned at random to each letter, with a probability of half being subject to the constraint that no more than four of the letters be lowercase. Similarly, in mixed-hue strings, red was assigned at random to each letter, with a probability of half being subject to the constraint that no more than four of the letters be red (with the nonred letters all being presented in green). In mixed-case, mixed-hue strings, lowercase and red were assigned randomly and independently to each letter, with a probability of half being subject to the constraints that no more than four letters be lowercase and no more than four letters be red. The purpose of these constraints was, of course, to ensure that mixed strings were actually mixed.

The present approach to constructing mixed-case strings differs, as far as we can tell, from the approaches used by other investigators of this manipulation. Most investigators have used strings in which cases alternate systematically, letter by letter (e.g., MaYaLI & HuMpHrEyS, 1996; mAyAIL eT aL., 1997), or have assigned cases to letters to systematically encourage or discourage the perceptual grouping of particular letters (e.g., the “pig” in “SpRiNg;” Humphreys, Mayall, & Cooper, 2003). Experiment 4 of this article addressed the latter possibility.

Stimulus Display and Response Collection

Personal computers equipped with noninterlaced monitors were used to collect data. Stimulus presentation and timing were controlled by Micro Experimental Laboratory software (Schneider, 1988). The participants responded by using the index and middle fingers of their right hands to operate the left and right arrow keys located in the lower right-hand corner of the keyboard.

The participants sat approximately 60 cm from the display monitor in Experiment 1. In Experiment 2, participants placed their chins in a chinrest that was positioned 40 cm from the display monitor. In Experiments 3 and 4, participants placed their chins in a chinrest that was positioned 60 cm from the display monitor. All stimulus strings were centered on a black background. At a viewing distance of 60 cm, the visual angle subtended by a six-letter string was 1.90°, horizontally. At a viewing distance of 40 cm, the horizontal visual angle was 2.86°.

In all four experiments, the luminances of all stimuli and backgrounds were the same: The red stimulus letters were 48 cd/m² ($R = 63$, $G = 12$, $B = 63$), the green stimulus letters were 48 cd/m² ($R = 0$, $G = 50$, $B = 0$), and the gray background was 48 cd/m² ($R = 48$, $G = 47$, $B = 42$). Michelson contrast values in all conditions were 0.

Procedure

For each presented item, participants were to respond “word” if the letter string was an English word and “nonword” otherwise; Allen, Smith, Lien, Grabbe, and Murphy (2005) and Allen, Smith, Lien, Weber, and Madden (1997) showed that typical college students knew most of even the very low frequency words. Responses were to

be made as rapidly as possible while maintaining accuracy. Stimuli were presented for 100 msec in Experiment 1 and 400 msec in Experiments 2–4. Response time (RT) was measured from stimulus onset to the participant’s press of a response key. The assignment of responses to response keys was balanced across participants.

Data Analysis

In each experiment, we excluded from analyses of RTs trials on which the RT was less than 100 msec or greater than 3,000 msec. This resulted in the exclusion of less than 1% of trials. These trials were treated as errors.

As our primary predictions concerned responses to words, the results of each experiment are reported in two sections: The first concerns responses to words, and the second concerns overall differences between responses to words and nonwords and responses to nonwords.

EXPERIMENT 1

Experiment 1 was designed to evaluate both of the main predictions of the basic multistream model: Same-case words should be recognized faster than mixed-case words; and for mixed-case words (but not for lowercase words), hue mixing should improve performance relative to monochrome presentation. The hybrid model postulates that the lowercase monochrome and lowercase mixed-hue items are processed by the MD stream, that the mixed-case monochrome items are processed by the ID stream, and that the mixed-case, mixed-hue items are processed by either or both of the BD and ID streams. Although the BD and ID streams have similar processing rates, RTs for mixed-case, mixed-hue words should depend on the faster of the BD and ID streams, and so responses to these items should, on average, be faster than responses to mixed-case monochrome words (see Raab, 1962).

Alternatively, if words are always formed using a single orthographic input channel—that is, if words are always formed from component letters (see, e.g., Coltheart et al., 2001; McClelland & Rumelhart, 1981)—then the effect of hue consistency should be the same for lowercase and mixed-case words.

Method

Participants

Twenty individuals participated.

Stimuli and Procedure

Four stimulus conditions were defined by whether stimulus strings were lowercase or mixed case and by whether they were monochrome (either all green or all red letters) or mixed red and green. These two stimulus characteristics were combined orthogonally. As described in the General Method, each stimulus was used in each of the four stimulus conditions: Each of the two 384-item stimulus sets described in the General Method—each consisting of 192 words and 192 nonwords—was divided into four groups of 96 items each; these were counterbalanced approximately across the four conditions (i.e., over participants, each word string was used in each of the four hue-type $\times$ case-type conditions). For any given participant, monochrome strings were all red or all green; this was balanced over participants.

Results

Table 3 shows mean RTs and error rates (ERs) for words and nonwords in each of the four stimulus conditions.

Table 3
Mean Response Times (RTs, in Milliseconds) and Error Rates (%E) With Standard Deviations in Experiment 1 by Case Consistency (Lowercase, Mixed Case), Hue Consistency (Monochrome, Mixed Hue), and Lexical Type (Words, Nonwords)

Case	Hue Type							
	Mono-chrome		Mixed Hue		Mono-chrome		Mixed Hue	
	RT	SD	RT	SD	%E	SD	%E	SD
Words								
Lowercase	673	120	673	114	10.3	5.0	10.5	5.7
Mixed case	746	134	724	123	19.0	10.6	17.5	12.6
Nonwords								
Lowercase	782	201	800	177	23.6	22.1	24.5	20.7
Mixed case	784	167	795	168	16.1	11.5	19.2	14.7

Word Analyses

Response times. RTs for lowercase words ($M = 673$ msec) were significantly faster than those for mixed-case words ($M = 735$ msec) [$F(1,19) = 78.75, p < .001$]. There was also a hue consistency $\times$ case consistency interaction [$F(1,19) = 6.65, p < .05$]. To interpret this interaction, we ran separate simple effect analyses for each level of case consistency. For mixed-case words, responses were faster for mixed-hue words ($M = 724$ msec) than for monochrome words ($M = 746$ msec) [$F(1,19) = 9.31, p < .01$]. However, for lowercase words, the effect of hue consistency was not significant [$F(1,19) = 0.00, p < .97$], reflecting the equality of RTs for mixed-hue ($M = 673$ msec) and monochrome ($M = 673$ msec) items.

Error rates. ERs showed that participants responded more accurately to lowercase words (ER = 10.4%) than to mixed-case words (ER = 18.2%) [$F(1,19) = 14.22, p < .001$]. The hue consistency $\times$ case consistency interaction was not statistically significant ($p = .48$).

Effect of Lexicality and Nonword Analyses

Response times. RTs for words ($M = 704$ msec) were faster than those for nonwords ($M = 790$ msec) [$F(1,19) = 12.96, p < .01$]. There was no hue consistency $\times$ case consistency interaction for nonwords analyzed separately ($p = .66$). Also, RTs for lowercase nonwords ($M = 791$ msec) did not differ significantly from those for mixed-case nonwords ($M = 789$ msec) [$F(1,19) = 0.01, p < .90$].

Error rates. On average, responses to words (ER = 14.3%) were significantly more accurate than those to nonwords (ER = 20.9%) [$F(1,19) = 5.88, p < .05$]. For nonwords, responses to mixed-case strings (ER = 24.1%) were more accurate than those to lowercase strings (ER = 17.7%) [$F(1,19) = 6.07, p < .05$]. For nonwords, there was no hue consistency $\times$ case consistency interaction ($p = .43$).

Discussion

In Experiment 1, case mixing slowed word recognition relative to lowercase presentation. This is consistent with the idea that lowercase words are recognized on the basis

of information carried by the faster MD stream, whereas mixed-case words are recognized on the basis of information carried by the slower ID and BD streams.

The results of this experiment showed a performance advantage for mixed-case, mixed-hue words relative to mixed-case monochrome words. This is most parsimoniously accounted for by statistical facilitation involving the ID and BD processing streams. Case mixing is presumed to prevent the MD (holistic) channel from forming a word-level code, so recognition of mixed-case items is presumed to be based on information that is carried by one or both of the BD and ID streams. When a stimulus word that cannot be processed by the MD stream contains both fine-detail information, to which the ID stream is sensitive, and a hue difference at a boundary, to which the BD stream is sensitive, this word should tend to be recognized faster than words processed by just the ID stream. This is precisely the pattern of results observed in Experiment 1.

Note that we employed isoluminant displays in this experiment, so luminance variation cannot account for the processing advantage for mixed-case, mixed-hue stimuli over mixed-case monochrome stimuli. Furthermore, this effect cannot be attributed to particular stimuli, because all stimulus items were used in each of the four stimulus string conditions.

The results of Experiment 1 are consistent with the predictions of the multistream model but not with those of models of visual word recognition, in which words are always formed from component letters (e.g., Coltheart et al., 2001). However, these earlier models could potentially accommodate these data by adding the more elaborate parallel encoding streams proposed here.

EXPERIMENTS 2 AND 3

One might be concerned that the overall accuracy rate in Experiment 1 was low—only 82%. Using physically isoluminant stimuli and background makes a lexical decision task challenging, but it is likely that the 100-msec letter-string presentation duration made the task so difficult that a 90% accuracy rate was unobtainable. To determine whether the relatively low accuracy rate observed in Experiment 1 was due to the brief exposure duration and whether the hue-consistency and case-consistency effects would be found under higher accuracy conditions, we increased exposure duration from 100 msec to 400 msec in all subsequent experiments.

A key assumption of the multistream model is that the visual system normalizes retinal images in order to overcome the “poverty of the stimulus” (Allen et al., 1995). If this assumption is correct, retinal size should not change the pattern of results obtained in Experiment 1, but increasing viewing distance (thereby decreasing retinal size) should result in overall longer latencies or lower accuracy (due to increased normalization processing relative to the situation in which retinal size is larger). Parish and Sperling (1991) suggested that the absolute spatial frequency of an object was critical in letter discrimination, but the present view is that the spatial frequency relative to the size of the object is the critical factor in visual word recognition. In order to

test this hypothesis, we used a 40-cm display distance from the participant's eye to the display monitor in Experiment 2 and a 60-cm display distance in Experiment 3.

Method

Participants

Twenty individuals participated in Experiment 2, and 16 individuals participated in Experiment 3.

Stimuli and Procedure

These were the same as in Experiment 1, except that exposure duration for all stimuli was 400 msec (rather than 100 msec), and a chinrest was used to control viewing distances. In Experiment 2, the viewing distance was 40 cm; in Experiment 3, the viewing distance was 60 cm.

Results

Table 4 shows mean RTs and ERs for words and nonwords in each of the four stimulus conditions for both Experiments 2 and 3.

Word Analyses in Experiment 2

Response times. RTs for lowercase words ($M = 626$ msec) were significantly faster than those for mixed-case words ($M = 671$ msec) [$F(1,19) = 99.66, p < .001$]. There was also a hue consistency $\times$ case consistency interaction [$F(1,19) = 61.86, p < .001$]. To interpret this interaction, we ran separate simple effect analyses by case consistency. For mixed-case words, responses were faster for mixed-hue words ($M = 662$ msec) than for monochrome words ($M = 680$ msec) [$F(1,19) = 7.54, p < .05$]. However, for lowercase words, the effect of hue consistency was significant [$F(1,19) = 9.73, p < .01$]—but in the opposite direction—reflecting longer RTs for mixed-hue ($M = 635$ msec) than for monochrome ($M = 617$ msec) items.

Table 4

Mean Response Times (RTs, in Milliseconds) and Error Rates (%E) With Standard Deviations in Experiment 2 (40-cm Viewing Distance) and Experiment 3 (60-cm Viewing Distance) by Case Consistency (Lowercase, Mixed Case), Hue Consistency (Monochrome, Mixed Hue), and Lexical Type (Words, Nonwords)

Case	Hue Type							
	Mono-chrome		Mixed Hue		Mono-chrome		Mixed Hue	
	RT	SD	RT	SD	%E	SD	%E	SD
Experiment 2								
Words								
Lowercase	616	120	635	114	9.3	1.3	7.1	0.8
Mixed case	680	134	662	123	10.9	1.4	12.6	1.2
Nonwords								
Lowercase	696	201	708	177	11.0	1.4	10.4	1.3
Mixed case	709	167	729	168	7.9	1.3	10.7	1.0
Experiment 3								
Words								
Lowercase	696	120	708	114	7.8	1.0	8.5	0.9
Mixed case	770	134	748	123	10.0	1.1	11.1	1.2
Nonwords								
Lowercase	774	201	793	177	9.9	1.1	8.6	0.9
Mixed case	811	167	836	168	9.6	1.1	9.0	1.2

Error rates. Error rates showed that participants responded more accurately to lowercase words (ER = 8.2%) than to mixed-case words (ER = 11.8%) [$F(1,19) = 13.67, p < .01$]. The hue consistency $\times$ case consistency interaction was not statistically significant ($p = .11$).

Word Analyses in Experiment 3

Response times. RTs for lowercase words ($M = 702$ msec) were significantly faster than those to mixed-case words ($M = 759$ msec) [$F(1,15) = 21.95, p < .001$]. There was also a hue consistency $\times$ case consistency interaction [$F(1,15) = 10.32, p < .01$]. To interpret this interaction, we ran separate simple effect analyses by case consistency. For mixed-case words, responses were faster for mixed-hue words ($M = 748$ msec) than for monochrome words ($M = 770$ msec) [$F(1,15) = 4.64, p < .05$]. However, for lowercase words, the effect of hue consistency was not significant [$F(1,15) = 2.03, p = .17$], reflecting the approximate equality of RTs for mixed-hue ($M = 708$ msec) and monochrome ($M = 696$ msec) items.

Error rates. ERs for lowercase and mixed-case words were not significantly different [$F(1,15) = 3.42, p = .08$]. The hue consistency $\times$ case consistency interaction was not statistically significant ($p = .34$).

Effect of Lexicality and

Nonword Analyses in Experiment 2

Response times. RTs for words ($M = 648$ msec) were faster than those to nonwords ($M = 711$ msec) [$F(1,19) = 31.40, p < .001$]. Also, there was a stimulus type (word, nonword) $\times$ case consistency interaction [$F(1,19) = 7.47, p < .05$], indicating that there was a larger case-mixing effect for words than for nonwords. There was no hue consistency $\times$ case consistency interaction for nonwords ($p = .45$). Also, RTs for lowercase nonwords ($M = 702$ msec) were faster than those for mixed-case nonwords ($M = 719$ msec) [$F(1,19) = 5.70, p < .05$].

Error rates. On average, accuracy of responses to words (ER = 9.98%) was approximately the same as that of responses to nonwords (ER = 10.0%) [$F(1,19) = 0.00, p = .96$]. For nonwords, accuracy of responses to mixed-case strings (ER = 10.7%) did not differ significantly from that of responses to lowercase strings (ER = 9.3%) ($p = .16$). For nonwords, there was no hue consistency $\times$ case consistency interaction ($p = .10$).

Effect of Lexicality and

Nonword Analyses in Experiment 3

Response times. RTs for words ($M = 730$ msec) were faster than responses to nonwords ($M = 803$ msec) [$F(1,15) = 15.79, p < .01$]. Also, there was a stimulus consistency $\times$ hue consistency $\times$ case consistency interaction [$F(1,15) = 6.17, p < .05$], suggesting that the case-mixing effect for monochrome nonwords was smaller than the case-mixing effect for words. There was no hue consistency $\times$ case consistency interaction for nonwords ($p = .56$). Also, lowercase nonwords ($M = 783$ msec) were responded to more rapidly than were mixed-case nonwords (824 msec) [$F(1,15) = 27.49, p < .001$].

Error rates. On average, accuracy of responses to words ($ER = 9.4\%$) did not differ significantly from that of responses to nonwords ($ER = 9.3\%$) [$F(1,15) = 0.01$, $p = .91$]. For nonwords, there was no main effect for case consistency ($p = .96$), and there was no hue consistency $\times$ case consistency interaction ($p = .86$).

Combined Analyses in Experiments 2 and 3 for Words Only

Response times. The same pattern of results persisted in the overall analyses as occurred with the separate analyses by experiment. There was a main effect for distance (40 cm, $M = 648$ msec; 60 cm, $M = 730$ msec) [$F(1,34) = 17.66$, $p < .001$]. There was also a main effect for case consistency [$F(1,34) = 72.61$, $p < .001$], and there was a hue consistency $\times$ case consistency interaction [$F(1,34) = 42.43$, $p < .001$]. The hue consistency $\times$ case consistency $\times$ viewing distance interaction did not reach statistical significance [$F(1,34) = 0.03$, $p = .86$].

Error rates. There was a main effect for case consistency [$F(1,34) = 14.11$, $p < .001$], but no other effects reached statistical significance.

Combined Analyses in Experiments 2 and 3 for Nonwords Only

Response times. There were main effects for distance [$F(1,34) = 7.76$, $p < .01$] and case consistency [$F(1,34) = 29.18$, $p < .001$], and there was also a case consistency $\times$ distance interaction [$F(1,34) = 4.54$, $p < .05$]. No other effects reached statistical significance. The case consistency $\times$ distance interaction occurred because there was a larger case-mixing effect at 60 cm ($M = 40$ msec) than at 40 cm ($M = 17$ msec).

Error rates. There were no significant effects for the analysis of nonword errors.

Discussion

The data from both Experiment 2 (40-cm viewing distance) and Experiment 3 (60-cm viewing distance) replicated the core results from Experiment 1: Responses to mixed-case stimuli were slower (and/or were less accurate) than responses to lowercase stimuli, and hue mixing facilitated performance for mixed-case words but not for words (or nonwords) presented in consistent lowercase letters. As was the case for Experiment 1, the stimuli and background were presented at the same luminance levels (physical isoluminance). Thus, these data indicate that there is a small but reliable processing advantage for mixed-case, mixed-hue words relative to mixed-case monochrome words, but that there is no such advantage from mixing hue in lowercase words. We believe that the most parsimonious interpretation of these results is that for lowercase stimuli, lexical decisions are based on output from the more rapid MD processing stream, whereas for mixed-case stimuli, decisions are based on output from the slower parvocellular pathway with its two component streams—the ID stream, which emphasizes details using a grayscale level of analysis, and the BD stream, which emphasizes hue contrasts. For the mixed-case, mixed-hue items condition, both the ID and BD streams are likely to be activated, and statistical fa-

cilitation can occur, whereas for mixed-case monochrome items, no hue contrast activates the BD stream, so only one processing channel is activated.

The multistream model also predicts that the MD, ID, and BD streams use normalization to “clean up” ambiguous stimuli for later recognition (or rejection). Whereas the latencies for Experiment 3 (60-cm viewing distance) were significantly longer than the latencies for Experiment 2 (40-cm viewing distance), the data from both experiments showed the same pattern of results across case mixing and hue mixing (i.e., the joint effects were the same). Consequently, these data are consistent with the notion that normalization had occurred (because the visual system had adjusted for retinal size, yet the same pattern of results was obtained), but that more normalization was required for longer viewing distances. Furthermore, these results are consistent with the idea that visual word recognition is based on spatial frequency relative to the size of the object rather than on the absolute object spatial frequency (e.g., Parish & Sperling, 1991).

EXPERIMENT 4

An alternative account of the effect of hue consistency on lexical decisions about mixed-case words that was observed in Experiments 1–3 is inappropriate letter grouping (Humphreys et al., 2003; Mayall & Humphreys, 1996; Mayall et al., 1997). Mayall et al. (1997) manipulated case-consistency and interletter spacing in stimuli presented in a naming task. In their Experiment 1, in which all stimuli were words, adding spaces between letters did not affect naming times for lowercase words and facilitated naming of alternating-case words. In their Experiment 2, in which both words and nonwords were presented, this pattern was replicated for words and was found for nonwords as well. For their Experiment 3, Mayall et al. (1997) noted that the usual case-mixing manipulation (including that of their Experiments 1 and 2) involved correlated alternation of case and size, and so included stimulus conditions that permitted examination of the separate effects of case mixing (without size mixing) and size mixing (without case mixing). Mayall et al. (1997) found that the disruption in performance with correlated mixing of case and size more than exceeded the separate disruptive effects of case mixing and size mixing. Examining just those stimulus conditions also found in their Experiment 2, the effect of spacing on words was replicated (facilitation of naming for mixed-case, but not for lowercase, words), although the pattern for nonwords was rather different (apparent slowing of naming of lowercase items by spacing, and no effect of spacing on mixed-case items).

Mayall et al. (1997) argued that the most parsimonious account of the case-mixing effect was inappropriate letter grouping: that letters in mixed-case strings that shared case (and size) were grouped perceptually, that this grouping interfered with performance, and that spacing—at least for words—undid this grouping, and with it the deleterious consequences of case mixing for performance.

The pattern of results of Mayall et al. (1997) is superficially similar to the pattern of results that we found for

hue mixing in lowercase and mixed-case strings. If inappropriate letter grouping is, in fact, the correct account of the results of Mayall et al. (1997), one might suppose that inappropriate letter grouping also adequately accounts for our results. However, it is not clear how this view would account for the different effects of hue mixing on lowercase and mixed-case words observed in the present experiments. If hue is a sufficiently powerful stimulus variable for ungrouping inappropriate letter groups in mixed-case strings, it seems that it should also be sufficiently powerful for subserving the formation of inappropriate letter groups in lowercase strings, thereby slowing performance. This did not occur in the first three experiments of our investigation.

In another pertinent study, Humphreys et al. (2003) varied the case and hue of letters within words and nonwords to determine the effect this had on the naming of "buried" or "embedded" words in which hue was mixed (e.g., "pig" in "spring," "SpRiNg," or "sPrInG"). Case mixing slowed whole-word naming but facilitated the naming of buried words that were presented in different hues (e.g., "p," "i," and "g" might be presented in red, and "s," "r," and "n" in green). Humphreys et al. concluded that case mixing impairs supraletter grouping (Mayall et al., 1997) and that case mixing facilitates the allocation of attention to subparts of words.

To address the inappropriate letter grouping account of the mixed-case, mixed-hue processing advantage observed in our Experiments 1–3, in the present Experiment 4 we added a spacing variable. For half of the trials, stimulus strings were unspaced, and for the other half, strings were spaced by adding a space between adjacent letters. If the case consistency $\times$ hue consistency interactions observed in Experiments 1–3 were the result of inappropriate letter grouping, this interaction should be attenuated or eliminated in the spaced condition relative to the unspaced condition. Alternatively, the prediction derived from the multistream model is that the same case consistency $\times$ hue consistency interaction should occur at each level of spacing, although one prediction of the multistream model is that adding spacing should add another level of required normalization, thereby increasing latencies and/or errors.

Method

Participants

Twenty individuals participated in Experiment 4.

Stimuli and Procedure

These were the same as in Experiment 3, except we added a spacing condition. That is, for half of the trials, the stimuli were identical to those employed in Experiment 3 (e.g., "datum"), and for the other half of the trials, a space was inserted between adjacent letters (e.g., "d a t u m"). The viewing distance was 60 cm, controlled by having participants use a chinrest. Over participants, every word and nonword occurred in both spaced and unspaced conditions.

Results

Table 5 shows mean RTs and error rates for words and nonwords in each of the eight stimulus conditions.

Word Analyses

Response times. RTs for lowercase words ($M = 769$ msec) showed a trend toward being faster than those for mixed-case words ($M = 797$ msec) [$F(1,19) = 2.65$, $p = .12$] (but see error data), and there was no main effect of spacing [$F(1,19) = 0.68$, $p = .42$]. The hue consistency $\times$ case consistency interaction, though, was significant [$F(1,19) = 5.91$, $p < .05$] (For lowercase monochrome words, $M = 765$ msec; for lowercase mixed-hue words, $M = 773$ msec; for mixed-case monochrome words, $M = 813$ msec; for mixed-case, mixed-hue words, $M = 780$ msec.) The hue consistency $\times$ case consistency $\times$ spacing interaction also showed a trend toward significance ($p = .07$). To interpret these data, we conducted simple-effects analyses at each level of case consistency. For mixed-case words, responses were faster for mixed-hue words ($M = 780$ msec) than for monochrome words ($M = 813$ msec) [$F(1,19) = 14.36$, $p < .01$]; this mixed-hue advantage was significant for both unspaced [$F(1,19) = 7.06$, $p < .05$] and spaced [$F(1,19) = 13.66$, $p < .01$] words. There was no hue consistency $\times$ spacing interaction ($p = .81$). However, for lowercase words, the hue consistency $\times$ spacing interaction was significant [$F(1,19) = 4.70$, $p < .05$]. To interpret this interaction, we examined the simple effect of hue consistency at each level of spacing. The effect of hue mixing was not statistically significant in either the spaced ($p = .69$) or the unspaced ($p = .19$) conditions. The trend toward a significant three-way interaction occurred because of the lowercase words, not the mixed-case words. For mixed-case words, there was a hue-mixing advantage for both unspaced and spaced trials; for lowercase words, there was a trend toward a mixed-hue disadvantage for unspaced trials, but a trend toward a mixed-hue advantage for spaced trials (see Table 5). Finally, the case mixing $\times$ spacing interaction was not significant ($p = .97$).

Table 5
Mean Response Times (RTs, in Milliseconds) and Error Rates (%E) With Standard Deviations in Experiment 4 (60-cm Viewing Distance) by Case Consistency (Lowercase, Mixed Case), Hue Consistency (Monochrome, Mixed Hue), Spacing (Spaced, Unspaced), and Lexical Type (Words, Nonwords)

Case	Hue Type							
	Mono-chrome		Mixed Hue		Mono-chrome		Mixed Hue	
	RT	SD	RT	SD	%E	SD	%E	SD
Unspaced Words								
Lowercase	756	90	777	58	8.7	1.7	7.5	1.3
Mixed case	811	85	777	48	10.0	2.2	10.2	1.4
Spaced Words								
Lowercase	775	82	769	53	7.7	1.8	7.7	1.5
Mixed case	815	59	784	55	1.2	1.6	4.6	2.4
Unspaced Nonwords								
Lowercase	774	80	787	83	5.6	1.2	5.4	1.3
Mixed case	796	83	810	85	6.2	1.6	4.6	1.1
Spaced Nonwords								
Lowercase	793	95	780	80	8.1	1.8	7.1	1.5
Mixed case	815	100	806	78	7.3	1.8	6.2	1.1

Error rates. Responses to lowercase words ($ER = 7.9\%$) were more accurate than those to mixed-case words ($ER = 11.5\%$) [$F(1,19) = 8.72, p < .01$]. None of the hue consistency $\times$ case consistency ($p = .31$), hue consistency $\times$ case consistency $\times$ spacing ($p = .59$), or case mixing $\times$ spacing ($p = .15$) interactions was statistically significant.

Effect of Lexicality and Nonword Analyses

Response times. RTs for words ($M = 783$ msec) were not significantly faster than those to nonwords ($M = 792$ msec) ($p = .41$). For nonwords, there was neither a hue consistency $\times$ case consistency interaction ($p = .77$) nor a hue consistency $\times$ case consistency $\times$ spacing interaction ($p = .92$). RTs for lowercase nonwords ($M = 783$ msec) were significantly faster than those for mixed-case nonwords ($M = 807$ msec) [$F(1,19) = 5.57, p < .05$]. For the nonwords, there was a hue consistency $\times$ spacing interaction [$F(1,19) = 6.04, p < .05$], but when these data were analyzed further by spacing type, there was no simple effect for hue consistency for either spaced or unspaced nonwords ($ps > .25$). The unspaced nonwords showed a trend toward a mixed-hue disadvantage, but the spaced nonwords showed a trend toward a mixed-hue advantage (for both lowercase and mixed-case nonwords).

Error rates. Responses to words ($ER = 9.7\%$) were less accurate than those to nonwords ($ER = 6.3\%$) [$F(1,19) = 14.75, p = .01$]. For nonwords, responses to mixed-case strings were approximately as accurate as responses to lowercase strings ($p = .49$), and there was no statistically significant hue consistency $\times$ case consistency interaction ($p = .63$) or hue consistency $\times$ case consistency $\times$ spacing interaction ($p = .71$).

Discussion

The data from Experiment 4 replicated the mixed-hue facilitation results for mixed-case words observed in Experiments 1–3. Indeed, this result was observed for both spaced and unspaced words. These results are inconsistent with an inappropriate letter grouping interpretation (e.g., Humphreys et al., 2003; Mayall et al., 1997), because inserting spaces between letters did not eliminate or attenuate the mixed-case, mixed-hue facilitation (relative to mixed-case monochrome presentation). However, these results are consistent with the predictions of the multistream model. That is, spacing should not appreciably affect hue mixing effects for mixed-case words.

The results of Experiment 4 differed from those of Experiments 1–3 in that the main effect for case mixing was not significant for RT, although this effect was significant for errors. This suggests that the faster MD stream may have been slowed by the spacing manipulation in Experiment 4 (requiring more normalization for the MD stream), but that it was still more accurate than the slower ID and BD streams.

GENERAL DISCUSSION

These experiments evaluated a model of human visual word recognition that integrates findings from investiga-

tions of macaque visual processing (Van Essen & Anderson, 1995; Van Essen et al., 1992) with an information-processing model (Allen & Emerson, 1991; see also Allen et al., 1995). Both the neuroscience and behavioral models assume that recognition is based on the spatial-frequency patterns of objects and postulate multiple processing channels. The word-level and letter-level channels of the hybrid model correspond roughly to the MD and ID streams, respectively, of the Van Essen and Anderson model, although, as we hypothesized, the BD stream could analytically process information involving hue contrasts. This combined model was termed the multistream model (see Figure 1).

There are two major differences between this framework and that of such local connectionist models as the dual-route cascaded model (Coltheart et al., 2001; see also McClelland & Rumelhart, 1981), or such distributed connectionist models as those proposed by Perry, Ziegler, and Zorzi (2007); Plaut, McClelland, Seidenberg, and Patterson (1996); Seidenberg and McClelland (1989); Zorzi, Houghton, and Butterworth (1998). First, in the multistream model, visual analysis is carried out by sets of spatial frequency filters, rather than by a set (or sets) of visual feature detectors. Second, the multistream model proposes multiple streams that process different aspects of the stimulus input, rather than just one stream (or multiple streams that process a single input in different ways).

The evidence presented by Peterzell and Teller (2000), who conducted a principal components analysis on log contrast sensitivities for seven spatial frequency levels of each of monochromatic and chromatic gratings, is consistent with the multistream model. Three principal components were interpreted as a chromatic component; a low-spatial-frequency, achromatic component; and a high-spatial-frequency, achromatic component. These plausibly correspond to the BD, MD, and ID streams, respectively, that we have argued are the pathways of visual word recognition.

Finally, although the model proposed by Bar (2004) was not designed to account for visual word recognition (but, rather, object recognition in natural scenes), this model includes a neural mechanism for more rapid recognition of highly familiar objects using lower spatial frequency (magnocellular pathway) than for that using higher spatial-frequency information (parvocellular pathway). Research reported by Li et al. (2002) provides additional evidence of the greater importance of global levels of representation than of local levels of representation in the recognition of animals. (Global recognition of whole animals did not require appreciable focused attention, but recognition of separate features of animals did.)

The experiments reported in the present article were designed to evaluate, using human information-processing methods, two specific predictions of the multistream model: In lexical decision, recognition of same-case words would be faster than recognition of mixed-case words; and for mixed-case words, recognition of words in which the hues of letters were mixed would be faster than recognition of words in which all letters had the same hue. These predictions were motivated by the proposal by Van Essen and Anderson (1995) that the parvocellular channel con-

sists of two branches—the ID stream and the BD stream, with the ID stream being responsible for processing fine-detail information, and the BD stream being responsible for processing stimuli that contain variability in hue—and that object recognition is based on the first-arriving information carried by these parvocellular channels (the ID and BD streams) and the magnocellular channel (the MD stream).

In the remainder of this section, we review evidence in favor of the multistream model and discuss alternative accounts of the results we have reported.

Empirical Evidence for the Multistream Model

In each of Experiments 1–4, lowercase words were recognized significantly faster or more accurately than mixed-case words. This is consistent with the hypothesis that the familiar spatial-frequency patterns of whole words are processed by the faster MD stream and that unfamiliar spatial-frequency patterns are processed by the slower ID (and, perhaps, BD) stream(s). Thus, these data are consistent with the hypothesis that both holistic and analytic perceptual objects are used in visual word recognition (also see Allen et al., 1995).

In each experiment, for lowercase words, hue mixing did not affect performance relative to monochrome presentation, but for mixed-case words, hue mixing improved performance relative to monochrome presentation. This facilitation of responding by hue mixing for mixed-case but not lowercase words is predicted by the multistream model. According to the model, only for mixed-case, mixed-hue words are both parvocellular streams active, and RT depends on the faster of the two parvocellular streams.

In Experiments 1–4, we showed that hue variation is essential to the mixed-case, mixed-hue effect: We mixed hues but controlled luminance so that there was no luminance variation and found the performance advantage for mixed-case, mixed-hue words relative to monochrome words. Therefore, hue variation, and not merely luminance variation, appears essential to the effect; our interpretation is that as assumed by the model, only when there is hue variation are both the ID and BD streams activated.

Inappropriate Letter Grouping

As noted earlier, Humphreys et al. (2003) and Mayall et al. (1997) proposed that case-mixing effects could be attributed to inappropriate letter grouping. They argued that the most parsimonious account of the case-mixing effect was that letters in mixed-case strings that share case (and size) are grouped perceptually, that this grouping interferes with performance, and that spacing, at least for words, undoes this grouping and with it the deleterious consequences of case mixing for performance. Data from Experiment 4, in which case consistency, hue consistency, and spacing were manipulated factorially, showed that inappropriate letter grouping could not account for the observed mixed-hue advantage for mixed-case stimuli because the effect occurred for both spaced and unspaced words. However, the present multistream approach is consistent with the design assumption of Humphreys et al., that humans encode whole words (at least, up to six to eight

letters in length; see Carr & Pollatsek, 1985) in parallel. Furthermore, we believe that our analytic pathways (the ID and BD streams—in which letter strings are encoded individually, but in parallel) are quite consistent with what Humphreys et al. and Mayall et al. (1997) propose as the single channel. Therefore, the point of disagreement is that we believe that a holistic channel is necessary, whereas Humphreys and colleagues do not. Nevertheless, both approaches share an emphasis on whole-word processing.

Lateral Masking

Previous investigators of the mixed-case disadvantage in visual word recognition have considered the possibility that it is due to lateral masking of lowercase letters by adjacent uppercase letters (e.g., Mayall et al., 1997). Both Mayall et al. (1997) and Humphreys et al. (2003) concluded that lateral masking could not account for their results. On this point, we agree. The lateral-masking interpretation cannot parsimoniously account for the joint effects of hue mixing and case mixing observed in the experiments reported in this article. Furthermore, the results from Experiment 4, in which the hue facilitation effect for mixed-case (but not lowercase) words was not affected by spacing, seem to be particularly inconsistent with a lateral-masking interpretation. Spacing should have at least attenuated any lateral masking.

Isoluminance

In many studies of the effect of hue on visual processing, researchers have controlled the luminance levels of all stimuli (e.g., Peterzell & Teller, 2000; Schiller, Logothetis, & Charles, 1991). In Experiments 1–4, we used isoluminant stimuli and background and observed the mixed-case, mixed-hue advantage relative to mixed-case monochrome. These results imply that this effect is due not to luminance variation but to hue variation.

Peterzell and Teller (2000) found three latent factors (corresponding to one chromatic and two monochrome channels) that appear to be analogous to the three cortical channels discussed in this article. Furthermore, Peterzell and Teller showed that performance using hue (red, green) isoluminance across seven different spatial frequencies was equivalent to that in three other conditions in which the relative luminance of red and green hues was varied. These results converge with the results of our experiments in supporting the existence of three visual channels for visual perception and word recognition.

However, it should be noted that physical luminance differences and perceived (subjective) luminance differences are not necessarily the same. Indeed, Jordan, Sherman, and Tonkin (2007) have shown that using subjective isoluminance has advantages over physical isoluminance. However, subjective isoluminance almost certainly varies not just across individuals, but also within individuals over time, so it may be that both physical and subjective measures of isoluminance are just approximations. Thus, the physical isoluminance control in the experiments reported in this article provides preliminary evidence that the hue-consistency effect we have observed is not due to luminance differences. Subjective isoluminance could

potentially provide an even more sensitive test of this possibility.

How Many Channels?

In this article, we have provided evidence that readers use three channels during visual word recognition. However, other evidence suggests that there may be many more distinct spatial-frequency “bands” that are used during visual word recognition (e.g., Patching & Jordan, 2005). There is significant overlap between magnocellular and parvocellular pathways in spatial-frequency bandwidth (e.g., the magnocellular pathway extends up to spatial frequencies of 3.5 cpd; Merigan & Maunsell, 1993), so there is no reason that both of these main pathways should not use multiple bands of spatial-frequency channels. The three channels postulated by the multistream model may be just the tip of the iceberg in terms of the actual number of channels used during visual word recognition.

A related potential problem with models of visual word recognition that emphasize magnocellular processing to encode global objects (such as the multistream model) is that there is accumulating evidence that individuals have more perceptual sensitivity to words presented in the 5- to 7-cpd spatial-frequency interval (parvocellular) than to those presented in the 1- to 3.5-cpd spatial-frequency interval (the approximate bandwidth of the magnocellular pathway) (Patching & Jordan, 2005). It does not appear that this is a major problem for the multistream model, however, because fine visual acuity is not hypothesized to be the forte of the MD pathway. Word recognition takes place over time, and a blurry stimulus can be encoded more rapidly than an object processed using higher spatial frequencies (Bar, 2004). That is, even if individuals have poorer perceptual discrimination of objects presented briefly with a low-spatial-frequency band-pass filter than with a higher spatial-frequency band-pass filter (Patching & Jordan, 2005), it appears that humans recognize these blurry objects faster than they do the higher spatial-frequency objects (e.g., Bar, 2004).

The reason that theoreticians seem to need the concept of global (holistic) and local (analytic or letter-level) channels involved in something like a stochastic race in which the global channel(s) is (are) biased to win is that global precedence has been observed both in brain-based studies, such as Bar (2004), and in behavioral studies, such as Li et al. (2002) and the present study. The usefulness of the magnocellular/parvocellular distinction is that the magnocellular visual pathway represents objects globally and is much faster than the parvocellular pathway, which represents objects locally. Even if this magnocellular/parvocellular distinction is not correct, such global precedence phenomena in visual word recognition as case-mixing effects, word superiority/inferiority effects (e.g., Healy, 1976; Reicher, 1969; Wheeler, 1970), and the non-monotonic effect of word frequency found when participants match letters with words (Allen & Emerson, 1991; Allen & Madden, 1990) must still be explained. The known channel dynamics of the magnocellular/parvocellular distinction allow us to account for global precedence effects

for which there is no other parsimonious explanation. The further extension of these pathways into three cortical channels (MD, ID, BD) allows us to account for the hue consistency and case consistency effects reported in the present article.

Do Models of Visual Word Recognition Need More Routes?

It is unclear to us how models of visual word recognition that use a single orthographic input channel in which words are formed from component letters (see, e.g., Coltheart et al., 2001; McClelland & Rumelhart, 1981; Perry et al., 2007) can account for the effects of case and hue mixing that we have reported without elaborating their prelexical mechanisms. Indeed, Mayall, Humphreys, Mechelli, Olson, and Price (2001), in a PET study, concluded that their imaging data were “consistent with the idea that case mixing mainly affects early stages of word recognition, and that increased processing at these early stages may allow normal processing in the later lexical stages involved specifically with language processing” (p. 850). This conclusion is fully consistent with the architecture of the multistream model.

We suggest that a whole-word (or at least multiletter) route and two analytic-input routes are needed. In the dual-route cascaded model of Coltheart et al. (2001) and the more recent connectionist dual-process (CDP+) model of Perry et al. (2007), both the lexical nonsemantic route and the grapheme-to-phoneme route process the same encoded input—the letters of the string, which are encoded in parallel. This is identical to the letter-level or analytical-input channel of the hybrid model (Allen & Emerson, 1991; Allen et al., 1995) and the parvocellular streams (ID, BD) of the multistream model. Interestingly, the earlier connectionist dual-process model of Zorzi et al. (1998) uses onsets and rimes (multiletter units), but these appear to be formed orthographically from features and component letters. (We suspect that individuals use this sort of multiletter encoding, and it would be interesting in future research to determine how this fared in computational modeling.) Without a holistic MD stream, an analytic, achromatic, fine-detailed stream (ID), and a second analytic stream that is sensitive to variation in hue (in the present model, the BD stream) that allows for statistical facilitation on certain mixed-case conditions, it is unclear how a dual-route or multiroute model of visual word recognition could account for the joint effects of case consistency and hue consistency (as well as spacing) observed in the present experiments.

Whether readers use whole words (up to, say, six to eight letters) or just multiletter units cannot be fully addressed with the present data. However, our results do appear to require that letter-level and either word-level or multiletter-level data be processed in a parallel stochastic race to recognition that is biased toward the holistic channel with familiar words. Indeed, there is not likely to be much functional difference between multiletter units of three or more letters and whole-word units. This is why the model proposed by Humphreys et al. (2003), with its em-

phasis on whole-word processing, has considerable similarities to the present multistream model. As Humphreys and colleagues have noted, their "PIG in sPrInG" data do not present a serious empirical threat to this type of hybrid model because, "if attention to the buried words is facilitated by case mixing, this may help performance here [in processing smaller words embedded in larger words], but not when the task requires reading at the whole word level" (Humphreys et al., 2003, p. 945).

Evidence for a Response Deadline

One pattern in the present data that challenges the primarily bottom-up multistream model is that nonwords did not show the same mixed-case, mixed-hue advantage as did words. It is possible that the participants used a response deadline that was frequently reached in classifying nonwords. Grainger and Jacobs (1996) argued that in lexical decision, a response deadline is used in classifying strings as nonwords; in the dual-route cascaded model of Coltheart et al. (2001), the response deadline is variable and is set according to the total amount of activation in the lexicon. Essentially, the response deadline accounts for how strings are classified as nonwords without an exhaustive search of the lexicon: If a string has not been classified as a word by the deadline, it is classified as a nonword. The results of the present experiments are consistent with a model of visual word recognition in which information in three input channels (MD, ID, BD) is in a stochastic race to recognition by a central processing unit; these data provide some evidence of the use of a response deadline to reject nonwords. Specifically, in Experiment 1, the processing disadvantage for RT for mixed-case letter strings was eliminated for nonword stimuli (see Table 3). This finding is consistent with the notion that quite different processing dynamics were involved in rejecting the nonwords in the present Experiment 1 than were used to recognize the words. For nonwords, recognition probably never occurred. Instead, these nonword items were rejected as words if they were not recognized before a response deadline passed.

Although the nonword RT data from Experiments 2 and 3 did show a case-mixing effect (suggesting that at least two of the hypothesized channels—the MD and ID—were being used to make nonword decisions), the effect of case mixing in the error data for nonwords was directionally the same as that in the RT data in Experiment 1. Namely, the effect of case mixing on errors was much stronger for words than for nonwords (see Table 4).

The stimulus conditions in Experiment 4 (spacing and case consistency manipulations resulted in just 25% of the words and nonwords being presented in familiar lowercase letters without spacing) appeared to prevent the use of a deadline procedure (as indicated by the finding that nonword RT was not significantly slower than word RT, and that nonword errors were significantly lower than word errors). Interestingly, the spaced nonwords in Experiment 4 (see Table 5) did show a trend toward a mixed-hue advantage for RT (for both lowercase and mixed-case stimuli). These results suggest that when a constant dead-

line procedure for nonwords cannot work, because many words will require a response deadline as long as that for nonwords due to high levels of whole-word stimulus unfamiliarity, nonwords may be processed more like words, so that there is evidence of a hue-consistency effect when the whole-word or multiletter MD channel cannot output a code due to lack of stimulus familiarity.

Developmental Effects

Although younger adults in the present four experiments consistently showed a mixed-case, mixed-hue advantage (relative to mixed-case monochrome presentation) for words, other studies have failed to observe this effect for cognitively healthy older adults (Allen et al., 2002) or for cognitively healthy older adults and older adults diagnosed with the amnesic type of mild cognitive impairment (Bush, Allen, Kaut, & Ogrocki, 2007). Allen et al. (2002) and Bush et al. used the same stimulus conditions as those used in Experiment 1 of this article. The finding that older adults do not show the same hue-mixing effects as younger adults suggests that older adults are even more holistically biased than are younger adults (Allen et al., 2002).

Conclusion

The results of these experiments, along with the work of Bar (2004), Jordan and colleagues (e.g., Jordan et al., 2003), Li et al. (2002), Peterzell and Teller (2000), and Van Essen and colleagues (Van Essen & Anderson, 1995; Van Essen et al., 1992) support the notion that multiple neural processing streams are involved in a stochastic race toward visual object recognition. The present data suggest that visual word recognition tends to be based on the holistic (MD) channel (Allen et al., 1995; Balota & Spieler, 1998; Spieler & Balota, 2000), although recognition can use information from the two analytic channels (ID, BD) if the stimulus information is sufficiently unfamiliar to the MD stream (e.g., for mixed-case stimuli; see also Jordan & Bevan, 1996). The redundancy of this system presumably serves to greatly increase reliability. If one system fails, another system's output can be used to solve the task at hand.

AUTHOR NOTE

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APPENDIX

Word and Nonword Pairs

List A

state/stote	being/deing	people/deople	united/unated
right/rught	while/whele	public/public	number/nimber
white/whate	point/poind	looked/dooked	called/colled
sense/sanse	thing/thung	itself/itsalf	church/charch
whole/wholt	hands/honds	cannot/bannot	really/seally
heard/meard	money/maney	office/offuce	became/becime
still/stell	world/wirld	around/arount	little/lottle
great/breat	since/sance	course/fourse	system/systim
later/loter	given/goven	social/docial	second/secand
light/dight	began/bogan	seemed/beemed	family/femily
human/homan	times/tumes	across/acruss	either/eithen
major/mijor	whose/whase	making/meaking	result/resolt
party/perty	clear/clead	figure/fogure	modern/modern
stood/stoon	leave/deave	ground/bround	nature/noture
lines/lunes	sound/tound	report/repart	except/axcept
union/enion	basis/bosis	higher/ligher	beyond/beyand
makes/mukes	miles/ciles	taking/tiking	county/rounty
moral/meral	bring/brang	likely/lokely	wanted/winted
front/frant	music/masic	mother/muther	strong/strang
child/cheld	total/tetal	needed/geeded	months/manths
third/thard	black/blick	person/herson	forces/furces
moved/muvd	wrote/wrate	walked/malked	indeed/ondeed
heart/leart	tried/bried	market/morket	growth/growth
floor/floon	trade/trode	answer/unsver	square/squart
grace/gruce	grass/gress	august/augast	create/treate
agree/agrel	award/awird	honest/hanest	denied/danied
spend/spond	prove/prave	player/pluyer	estate/estite
faced/ficed	pilot/palot	forget/farget	screen/screet
dozen/dazen	count/bount	minute/manute	surely/sarely
begun/bigun	hardy/herdy	widely/wodely	safety/sofety
angle/ungle	occur/occun	muscle/mascle	listen/lesten
phone/phane	chest/chast	abroad/abroan	breath/preath
agent/agint	crowd/prowd	bureau/sureau	handle/hondle
reply/deply	prime/promo	liquid/loquid	choose/choise
route/soute	plain/plair	pocket/pecket	anyway/unyway
skill/skall	rapid/ropid	lovely/lavely	smooth/spooth
icing/ocing	adapt/adipt	disarm/diserm	defect/difect

APPENDIX (Continued)

foggy/figgy	digit/dogit	banter/binter	beacon/meacon
canon/canin	stabs/stebis	comply/camply	adhere/adherd
badge/bedge	fined/foned	dismay/dosmay	bedlam/badlam
facet/ficet	brush/brush	humane/humine	casino/cusino
coral/curel	madly/mudly	stripe/strope	nugget/nagget
ached/eched	batch/betch	decree/ducree	addict/addect
décor/dacor	lofty/lifty	abound/about	acorns/acerns
ether/ethen	stale/stule	sailor/sailon	wolves/wilves
filth/falth	nooks/dooks	beckon/backon	ferret/farret
inert/inart	crook/prook	caress/curess	parcel/porcel
leash/reash	heron/heran	enrich/unrich	scanty/scunty

List B

found/lound	those/thise	before/beford	during/doring
small/smill	house/couse	enough/anough	though/shough
later/nater	group/groul	things/thungs	toward/soward
think/thonk	power/powen	gotten/gatten	within/withen
today/foday	words/werds	behind/rehind	action/oction
taken/daken	study/stady	change/chonge	street/streed
where/whare	never/bever	should/chould	school/schoop
place/ploce	sight/dight	almost/almost	always/ilways
sight/dight	going/moing	rather/rother	better/botter
least/leace	large/narge	turned/hurned	become/recome
death/meath	field/rield	having/baving	period/heriod
known/knawn	shall/shull	reason/teason	moment/poment
voice/voibe	court/mourt	common/dommon	policy/rolicy
class/blass	north/nerth	rather/nather	values/calues
women/wamen	space/spoce	inside/unsid	amount/amound
hosts/dosts	hours/nours	passed/passet	island/island
river/siver	doing /loing	polite/polide	simply/samply
birth/barth	final/finam	better/retter	effort/affort
close/clase	level/lavel	future/foture	living/siving
leave/leace	short/chort	return/returb	longer/langer
alone/alune	value/falue	coming/boming	recent/lecent
brown/brewn	stage/stoge	single/ringle	spirit/sparit
terms/tarms	shown/shewn	trying/brying	center/menter
story/stery	range/ringe	points/foints	entire/antire
chair/chail	opera/apera	burden/barden	noddod/nidded
sound/gound	flash/flish	lawyer/dawyer	stream/streal
guard/guarb	raise/raist	pounds/lounds	dollar/mollar
tired/rired	worse/warse	advice/advoce	strike/strake
limit/dimit	royal/noyal	easier/eanier	silent/solent
pages/mages	hoped/haped	wisdom/wisdor	atomic/atomic
loose/roose	depth/dopth	normal/gormal	burned/curned
angry/engry	humor/sumor	mantle/mintle	target/torget
boats/loats	enjoy/enjay	aspect/aspoct	symbol/symbol
views/piews	drama/drima	native/pative	golden/galden
sorry/morry	grown/grown	mobile/mabile	cousin/rousin
brain/brait	trend/trond	visual/fisual	unable/inable
mirth/morth	weave/neave	teller/tuller	minge/monge
flops/fleps	booty/rooty	reflex/meflex	panted/pantel
ethic/ethac	salve/malve	portal/partal	staple/stople
dined/bined	tapes/lapes	beware/seware	corked/horked
canal/canel	renew/fenew	delays/deloys	libido/labido
bicep/bicup	cores/jores	calico/halico	bigots/rigots
grape/prape	paled/raled	cosmos/casmos	deport/duport
plush/plosh	pedal/pidal	hounds/lounds	patron/natron
bends/hends	modal/mudal	garter/harter	forage/lorage
gusto/gisto	chunk/chank	rustic/rastic	bordel/bardel
comma/lomma	fairy/nairy	remake/semake	trance/trence
datum/gatum	haunt/baunt	embark/imark	nectar/noctar