Using spatial frequency adaptation to study word recognition

TIMOTHY R. JORDAN

University of Leicester, Leicester, England

SUSAN M. SHERMAN

Keele University, Keele, England

AND

GEOFFREY R. PATCHING

University of Stockholm, Stockholm, Sweden

The study of spatial frequency is being used increasingly often to investigate processes underlying visual word recognition. However, research in this area has adopted techniques that require the physical deformation of word targets used in experiments (e.g., filtered images of words, words embedded in visual noise), and this approach may limit the inferences that can be made about the role of spatial frequencies in normal word recognition. *Spatial frequency adaptation* is described in this article as an additional technique for studying the role of spatial frequency information in word recognition. The advantage of this technique is that it alters participants' sensitivity to particular spatial frequencies and so allows the study of spatial frequency involvement in word recognition using normal images of word stimuli. The application of the adaptation technique to studies of word recognition is explained in detail and its potential is then demonstrated by an example word recognition experiment in which spatial frequency adaptation was used.

Since the beginning of scientific research in visual word recognition (e.g., Cattell, 1885), numerous techniques have been used to elucidate the processes underlying this fundamental aspect of human ability. For example, researchers have used (1) *whole report*, in which the identity of each entire stimulus is reported (e.g., Balota, Cortese, Sergeant-Marshall, Spieler, & Yap, 2004; Cattell, 1885; Jordan, Thomas, & Scott-Brown, 1999; Mayall, Humphreys, Mechelli, Olson, & Price, 2001); (2) *lexical decision*, in which presentations of character strings are categorized as words or nonwords (e.g., Barber, Vergara, & Carreiras, 2004; Borowsky & Besner, 1993; Forster & Veres, 1998); (3) the *Reicher-Wheeler task* (after Reicher, 1969; Wheeler, 1970), in which brief presentations of letters, words, pseudowords, or nonwords are followed by two response alternatives that are equally likely to have appeared as the target (e.g., Grainger, Bouttevin, Truc, Bastien, & Ziegler, 2003; Hooper & Paap, 1997; Jordan & Bevan, 1996); (4) *priming*, in which a stimulus with particular visual, orthographic, or semantic characteristics is presented directly before a target that must then be identified (e.g., Jordan, 1986; Perea & Lupker, 2004; Rastle & Coltheart, 1999); and (5) *letter detection*, in which a particular letter must be detected in a body of text or a single string (e.g., Allen, Stadlander, Groth, Pickle, & Madden, 2000; Gross, Treiman, & Inman, 2000; Healy, 1994). By carefully ma-

nipulating the experimental variables used in these and other techniques, researchers have made inferences about the processes underlying word recognition, and these inferences have led to numerous models designed to account for human word recognition performance (e.g., Coltheart, Rastle, Perry, Langdon, & Ziegler, 2001; Grainger & Jacobs, 1996; McClelland & Rumelhart, 1981; Paap, Newsome, McDonald, & Schvaneveldt, 1982).

However, models of word recognition generally place considerable emphasis on the role of highly refined visual input, such as letter fragments and individual letters, and overlook the more basic visual characteristics of words, such as their spatial frequency content. In contrast, an alternative approach to understanding word recognition incorporates the notion that the visual world can be described in terms of individual spatial frequencies, with high-spatial-frequency content referring to small objects or local structure and low-spatial-frequency content referring to large objects or global structure (e.g., Ginsburg, 1980, 1986). Thus, when applied to the study of word recognition, experiments that address the role of spatial frequency analyses, rather than the identification of letter fragments or letters, may provide important additional clues to the processes underpinning human word recognition (e.g., Allen, Wallace, & Weber, 1995; Jordan, 1990, 1995; Jordan, Patching, & Thomas, 2003a, 2003b; Patching & Jordan, 2005).

T. R. Jordan, prof.timjordan@leicester.ac.uk

Support for the use of spatial frequency information during word recognition comes from two lines of research. The first uses band-pass-filtered images in which text or single words are filtered into narrow bands centered on a particular spatial frequency and from which other spatial frequencies have been removed (e.g., Leat & Munger, 1994; Patching & Jordan, 2005). The logic behind this approach is that if word recognition suffers when certain spatial frequencies have been removed from a word target, these frequencies are likely to be important for word recognition. A second line of research uses images in which visual noise frequencies are added to word targets to produce simultaneous masking (e.g., Majaj, Liang, Martelli, Berger, & Pelli, 2003; Pelli, Farell, & Moore, 2003). The logic behind this approach is that if word recognition suffers when certain noise frequencies are added to the image of a word target, these frequencies are likely to be important for word recognition.

These studies provide valuable clues to the role of spatial frequencies in word recognition. However, one aspect of using filtering and noise is that both techniques involve changes to the physical characteristics of stimuli, and these changes are obvious to participants. This has implications for an accurate understanding of the role of spatial frequencies in processing normal (unadulterated) words. In particular, it is not clear that the processing inspired by an adulterated word target is normal, with the exception of processing the spatial frequencies that have been removed or masked by noise. Instead, adulterated word targets may inspire participants to deliberately place abnormal strategic emphasis on those aspects of the image that are not adulterated, and so provide a distorted indication of the importance of the spatial frequencies that can still be processed and those that cannot. As a consequence, using normal, unadulterated word stimuli and finding other effective but subjectively less obvious ways to alter participants' perception of the spatial frequency content of word stimuli would provide a useful development for investigating the role of spatial frequencies in word recognition.

It is well established that when observers receive prolonged exposure to a particular spatial frequency grating

(a pattern with light and dark bars alternating for a given spatial frequency; see Figure 1), their visual sensitivity to the spatial frequency contained within the grating is suppressed (Blakemore & Campbell, 1969; see also Baccus & Meister, 2002, 2004; Gardner et al., 2005; Greenlee & Heitger, 1988; Solomon, Peirce, Dhruv, & Lennie, 2004). This effect, called *spatial frequency adaptation*, provides a new approach to studying the influence of spatial frequencies on word perception. In particular, using adaptation to suppress sensitivity to particular spatial frequencies offers the advantage of changes in visual ability that are indiscernible to participants and that would allow the relative importance of different spatial frequencies in word recognition to be investigated using normal (unadulterated) stimuli presented after adaptation has occurred.

Close inspection of the literature reveals no research that has applied the spatial frequency adaptation paradigm to the study of word recognition (although one study has used spatial frequency adaptation to investigate the identification of single letters [Chung, Levi, & Tjan, 2003] and others have investigated effects of reading text on perception of spatial frequencies [Lunn & Banks, 1986; Magnussen, Dyrnes, Greenlee, Nordby, & Watten, 1992; Mikaelian, 1988; Pelli, 1989]). Accordingly, the purpose of the present article is to present the spatial frequency adaptation paradigm as a method of investigating spatial-frequency-dependent processes in word recognition and to provide advice on how best to implement this procedure. We then describe an experiment in which the procedure was used to investigate the effects of spatial frequency adaptation on word recognition.

Adaptation Stimuli

Several types of spatial frequency gratings are contenders for adaptation stimuli, of which probably the best known are *square wave*, *sinus wave* or *sinusoidal*, and *Gabor* (see Figure 1). Square-wave gratings are composed of alternating bars of uniformly high and low luminance. Sinusoidal gratings are refinements of square-wave gratings and contain a gradual transition from low to high luminance in a sinus-like

Figure 1. Examples of spatial frequency gratings that may be used for adaptation stimuli: (a) square wave, (b) sinus wave or sinusoidal, and (c) Gabor.

way. This modification is of considerable theoretical significance because each visual image can be decomposed into a weighted sum of sinusoidal gratings of different spatial frequency and phase (Fourier analysis). Such decomposition implies that sinusoidal gratings reflect more precisely the spatial frequency channels underlying the processing of the visual system. Moreover, a square-wave grating can be decomposed into a weighted sum of sinusoidal gratings, which means that the former has the disadvantage of being less spatial frequency selective. Indeed, Blakemore and Campbell (1969) showed that adaptation to a square-wave grating resulted in two separate suppression effects, one for the fundamental spatial frequency of the grating and one for the third harmonic of the grating. Gabor gratings are a refinement of the sinusoidal grating because Gabors contain an additional multiplication with a Gaussian distribution. The effect of this multiplication is that the contrast between high and low luminance gradually fades from the center of the grating toward the perimeter and so removes high-contrast edges at the perimeter that would otherwise produce problems with spurious spatial frequencies that resonate with the problems associated with square-wave gratings already discussed.

Consequently, Gabor gratings are the best adaptation stimuli for studying the effects of spatial frequency adaptation on perception of word targets. However, the effectiveness of these gratings as adaptation stimuli will be affected by their luminance contrast (the difference between the light and dark bars), and evidence indicates that high-contrast gratings produce the greatest adaptation (e.g., Foley & Boynton, 1993; Greenlee, Georgeson, Magnussen, & Harris, 1991). Once the contrast for the Gabor gratings used as adaptation stimuli has been determined, the effectiveness of all adaptation stimuli in the experiment should be measured against a nonadaptation control condition in which each Gabor is replaced by a homogeneous (blank) field of the same size and space-averaged luminance as the adaptation stimuli.

Avoiding Afterimages

Precautions must also be taken to suppress the occurrence of retinal afterimages produced by the adaptation stimulus. The concern here is that if participants fixate any steady pattern for a sufficiently long period of time, a persistent negative version of the pattern is likely to be experienced due to retinal fatigue (e.g., Jones & Tulunay-Keesey, 1975; Marriott, 1965; Smith, 1977). If such a retinal afterimage were produced, the actual effect of spatial frequency adaptation on perception of a subsequently presented target word may be obscured by essentially a form of simultaneous masking.

Several ways have been proposed to prevent afterimages occurring in the adaptation paradigm. One way is to instruct participants to move their eyes across the adaptation grating so that retinal receptors are not fatigued by constant stimulation (e.g., Blakemore & Campbell, 1969; Magnussen & Greenlee, 1985). However, Smith (1977) has argued that this method does not completely eliminate afterimages for adaptation stimuli of below 3–4 cpd. Moreover, other evidence suggests that instructions alone do not determine the pattern of eye movements actually

implemented by participants (e.g., Jordan & Patching, 2006; Jordan, Patching, & Milner, 1998; Jordan, Patching, & Thomas, 2003a, 2003b). Consequently, a better approach is to alter the retinal location of the components of each grating by randomly varying the onscreen characteristics of the stimulus. This can be done by flickering the grating (by reversing the luminance of the bars; called counterphase modulation) or by having the bars of the grating drift laterally on the screen within the parameters of the grating's location, or by changing the screen location of the entire grating (e.g., Jones & Tulunay-Keesey, 1975; Marriott, 1965; Smith, 1977). However, the success of each of these procedures in preventing afterimages relies on participants not realigning their fixation with each shift in the components of each grating so that a constant retinal image is maintained for longer than is required. From the findings of Smith, random shifts that occur every 200 msec or less produce adaptation that is not influenced by the formation of afterimages.

Adaptation Timing

The effectiveness of an adaptation stimulus at producing adaptation is also affected by other timing characteristics of the adaptation paradigm. In particular, both the buildup of and recovery from adaptation have been reported to follow power functions of time (Greenlee et al., 1991; Magnussen & Greenlee, 1985; Rose & Evans, 1983), although other nonlinear relationships have been observed (e.g., Foley & Boynton, 1993). A number of studies suggest that recovery from adaptation is broadly proportional to the duration of the adaptation period (e.g., Blakemore & Campbell, 1969; Blakemore, Muncey, & Ridley, 1973; Bodinger, 1978; Heggelund & Hohmann, 1976; Magnussen & Greenlee, 1985; Rose & Lowe, 1982). For example, Magnussen and Greenlee (1985) found that adaptation reached its maximum level after 30–60 min of adaptation, with subsequent recovery from adaptation taking about equally long. Foley and Boynton (1993) and Georgeson and Georgeson (1987), however, argued that (near-) maximum adaptation is reached after a fraction of a second (<200 msec) of adaptation, the difference between their findings and those of Magnussen and Greenlee (1985) apparently being due to lag in measurement after adaptation offset. The general indication, therefore, is that longer adaptation periods can extend the adaptation effect but will not substantially elevate the level of adaptation that occurs. However, if presentation of experimental stimuli is not carried out immediately after adaptation offset, some recovery from adaptation may occur, although the rate of recovery will be slower when longer exposures to adaptation have been used.

In view of these timing considerations, how should the adaptation paradigm be implemented for studying word recognition? First, the longevity of the adaptation effect should be maximized by adapting participants for a substantial period (at least several minutes) at the start of the experimental session. To avoid effects of forward masking between adaptation and experimental stimuli (e.g., Foley & Boynton, 1993), a brief blank interval (of at least 100 msec; e.g., Keyser & Perrett, 2002) should then be used between the offset of the adaptation stimulus and the onset of the

first experimental stimulus.¹ From the evidence already described, this procedure is likely to provide adaptation for durations similar to the duration of the adaptation period, although the adaptation effect will deteriorate over time.

Clearly, careful counterbalancing of the order in which stimuli from different experimental conditions (e.g., words, nonwords) are presented after adaptation has taken place is required to ensure no systematic differences in the levels of adaptation that are present for each condition. However, higher levels of adaptation can be maintained throughout an experiment by "top-up" adaptation sessions between experimental trials that compensate for the adaptation loss that would otherwise occur. Note, however, that this procedure may not compensate exactly for any loss of adaptation effect, because this loss will be affected by the duration of the initial adaptation period, the duration of the top-up period, and the duration of any intervals between adaptation stimuli and targets. Therefore, if it is important that the same level of adaptation exists across an entire experiment, a preliminary experiment will be required to establish the appropriate temporal parameters for the adaptation stimuli and experimental displays that are ultimately used. Doing exactly this, Foley and Boynton (1993) found that when the initial adaptation period lasted for 2 min, and each adaptation top-up period was separated by an interval of 2 sec (during which time experimental targets were shown), adaptation top-up periods lasting 2 sec maintained the same level of adaptation throughout the experiment. The periods used (but not normally explicitly motivated) by other researchers for the initial adaptation period and for the duration of each top-up are usually also in the order of several minutes and several seconds, respectively (e.g., Heinrich & Bach, 2002; Suter, Armstrong, Suter, & Powers, 1991).

Finally in this section, when comparing effects of adaptation across a range of different spatial frequencies, a sensible precaution is to present each adaptation frequency in a separate session, and a sufficient recovery period should be allowed between sessions for the effects of adaptation to end. The precise time required for recovery will depend on the adaptation procedure used. However, from the findings of Magnussen and Greenlee (1985), an intersession lag equal to at least the total period of adaptation used in a session (i.e., the duration of the initial period of adaptation or, if top-up periods are also used, the total duration of all periods of adaptation) is a good estimate.

Preliminary Assessment of Adaptation Stimuli

The extent of adaptation produced by an adaptation stimulus can offer insight into the role of spatial frequency analysis in word recognition beyond the adaptation frequency actually used (e.g., Blakemore & Campbell, 1969; Heinrich & Bach, 2002; Mecacci & Spinelli, 1976; Snowden, 1994). For example, Blakemore and Campbell (1969) found that spatial frequency sensitivity may be suppressed not only for the frequency used for adaptation but also for spatial frequencies close to this frequency. In addition, it has been suggested that the spatial frequency sensitivity suppressed most by adaptation may be shifted away from the adaptation frequency to the nearest frequency channel of peak sensitivity (Suter et al., 1991), where it is assumed that there are only a

limited number of such channels available in the visual system (e.g., Watson & Robson, 1981). It may also be possible that sensitivity to certain spatial frequencies is facilitated because of a reduction in inhibition produced by the adapted frequency (De Valois, 1977; Suter et al., 1991).

It is therefore important to assess, ideally in a preliminary assessment session, the effect of each adaptation stimulus (including the nonadaptation control) on spatial frequency sensitivity in order to determine more precisely the effect of adaptation on word recognition. A well-established method of assessing spatial frequency sensitivity is to use a two-alternative forced choice task in which a spatial frequency stimulus (e.g., a Gabor) is presented to either the left or right of the center of a screen, and participants are required to decide on which side the stimulus was presented. By using a range of spatial frequency stimuli and the QUEST algorithm (Watson & Pelli, 1983) to adjust the contrast of each frequency to threshold, sensitivity to different spatial frequencies can be determined. By conducting the sensitivity assessment after exposure to each adaptation stimulus (and the nonadaptation control) used in the experiment proper, the effect of each adaptation stimulus on spatial frequency sensitivity can be determined and used to interpret fully the pattern of adaptation effects on word recognition observed in the experiment.

In line with these procedures, and to demonstrate the effectiveness of the adaptation technique for studying word recognition, an experiment is reported that applied the adaptation technique to a word recognition task in which stimuli were presented briefly for identification.

METHOD

Participants

Twenty paid undergraduate students between the ages of 18 and 35 years participated in the experiment. All were native speakers of British English, reported normal or corrected-to-normal vision, and were screened using a Bailey-Lovie eye chart (Bailey & Lovie, 1976) for minimum binocular acuity of 10/10 (3/3) or better.

Adaptation Stimuli

Each adaptation stimulus was a high-contrast, grayscale, vertically oriented Gabor grating of either 1, 2, 4, or 8 cpd.² Each Gabor subtended 18.5° in diameter. A homogeneous field of the same size and space-averaged luminance as the adaptation stimuli (including the same graded luminance profile from center to perimeter) acted as a nonadaptation control. A small but clearly visible dot was presented in the middle of each Gabor and the adaptation control. To prevent the formation of afterimages, each Gabor (and the nonadaptation control) was displayed for 200 msec in one screen location and then moved instantaneously horizontally to a different screen location. The location of each shift was randomly determined with excursions of between $\pm 0.30^\circ$ and $\pm 3.60^\circ$. The center of each Gabor and the adaptation control always had the same vertical coordinate as the horizontal midline of each word and always remained horizontally within the central 3.60° of the screen.

Experimental Stimuli

Stimuli for the word recognition experiment consisted of 48 pairs of six-letter words. An additional 12 pairs of six-letter words were constructed to provide practice trials at the beginning of each session. The Reicher-Wheeler paradigm was used to suppress systematic effects of guesswork on performance (Reicher, 1969; Wheeler, 1970) and so words in each pair differed by just one letter in the same

position (e.g., *sample, simple*). Participants had to decide which word had been presented on each occasion by selecting the appropriate member of each matched pair. The location of the critical letter varied randomly across pairs, with the constraint that critical letters appeared in each letter position an equal number of times.

Apparatus

All stimuli were presented on a gamma-corrected Sony Trinitron GDM-F520 display monitor. A Cambridge Research Systems VSG 2/5 card controlled stimulus presentations and timing. Responses were collected via a Cambridge Research Systems CT3 button box. Luminance was measured using an optical photometer. The experiment was conducted in a sound-attenuated and darkened room, and displays were observed through a viewing hood fixed to the monitor, to ensure a constant viewing distance and to eliminate extraneous light.

Visual Conditions

The monitor was viewed from a distance of 57 cm and had a viewable area of 29° horizontally and 23° vertically. Background illumination of the monitor screen was 30 cd/m², and the space-averaged luminance of each Gabor and the nonadaptation control was 35 cd/m². Words were presented in a black 14-point Times New Roman font and subtended a horizontal visual angle of approximately 1.50°. Luminance of the experimental stimuli was 0.15 cd/m².

Design

Participants took part in five 75-min sessions, each one on a different day. Sessions of 75 min permitted uninterrupted assessment of the effects of each adaptation stimulus, and having just one session per day ensured an adequate recovery period from previous adaptation effects. A different adaptation condition (control, 1, 2, 4, or 8 cpd) was used in each session, counterbalanced across participants. Word stimuli were presented in pseudorandomly constructed cycles of 12 items, counterbalanced across critical-letter position. Each session was divided into two sections (practice, experimental), with no obvious transition from one section to the next.

Procedure

At the beginning of their first session, each participant was given written instructions informing him or her of the task and of the importance of responding as accurately as possible. At the start of each session, the adaptation field (control, 1, 2, 4, or 8 cpd) for that session was presented for 3 min before the presentation of the first target word. Subsequently, the adaptation field was presented for 5 sec before each target word. Following each adaptation field, a blank screen was displayed for 100 msec, followed by a word presented for 44 msec, followed by a blank screen for 100 msec. Two choices were then shown (the target and its matched alternative, e.g., *sample, simple*), randomly positioned one above the other at the center of the screen. Participants had to indicate which of these two alternatives had been shown by pressing one of two keys to select either the upper or lower alternative.

When questioned at the end of the experiment, all participants reported no change in their ability to process words after adaptation, and all expressed surprise when informed of the findings of the experiment.

Preliminary Assessment of Adaptation Stimuli

Before the experiment was conducted, the adaptation characteristics of the adaptation stimuli used in the experiment were assessed for 20 participants from the same population as the participants taking part in the experiment and using the same apparatus, adaptation stimuli, and visual conditions. The contrast sensitivity for each of 8 test spatial frequencies (0.5, 1, 2, 4, 6, 8, 10, 12 cpd) was assessed after exposure to each adaptation stimulus (1, 2, 4, and 8 cpd) and the nonadaptation control. Pretesting had established that exposure to the nonadaptation control produced no change in spatial frequency sensitivity.

The contrast sensitivity for the 8 test frequencies was determined using a spatial two-alternative, forced-choice task in which partici-

pants had to decide on which side of the monitor a Gabor stimulus was presented. At the start of each trial, an audible "bleep" was emitted from the button box to inform participants that a Gabor stimulus was about to be presented. Each Gabor was presented so that its center fell 10° to the left or right of the center of the screen on the horizontal midline. Each Gabor stimulus was presented 80 times, randomly interleaved, giving a total of 640 trials. On each trial, the contrast of each Gabor was determined using the QUEST algorithm (Pelli & Farell, 1994; Watson & Pelli, 1983) in the Psychophysics Toolbox (Brainard, 1997; Pelli, 1997). The threshold was set at 0.82 and the initial contrast of each Gabor was set at the average threshold contrast obtained from pilot studies. Contrast sensitivity was assessed in a separate session for each adaptation condition (each session on a different day), and the order of these sessions was counterbalanced across participants.

The adaptation procedure matched the adaptation procedure in the experiment. In particular, each session began with a 3-min adaptation period during which one of the 4 adaptation stimuli or the nonadaptation control was presented, followed by the first test Gabor. Subsequently, each test Gabor was preceded by a 5-sec exposure to the same adaptation stimulus. Contrast sensitivity scores were derived by taking the reciprocal of the contrast thresholds.

RESULTS

The data for the preliminary assessment of adaptation stimuli were calculated for each of the 8 test frequencies as difference scores between the contrast sensitivity obtained for the nonadaptation control condition and for each of the 4 adaptation stimuli (1, 2, 4, 8 cpd). The means of these differences, which all showed suppressed sensitivity when adaptation stimuli were used, are shown in Figure 2. These data were analyzed using a repeated measures ANOVA with two within-subjects factors of adaptation frequency (1, 2, 4, 8 cpd) and test frequency (0.5, 1, 2, 4, 6, 8, 10, 12 cpd). The analysis revealed main effects of adaptation frequency [$F(3,57) = 9.23, p < .001$] and test frequency [$F(7,133) = 4.48, p < .001$], and an interaction between these two factors [$F(21,399) = 3.76, p < .001$]. The key findings revealed by Tukey tests showed that, for each adaptation frequency, test frequencies that matched the adaptation frequency showed the most suppression (all $ps < .01$) and test frequencies adjacent to the adaptation frequency showed more suppression than all other test frequencies (all $ps < .01$). In addition, adaptation to 4 and 8 cpd produced higher peaks in suppression than adaptation to 1 and 2 cpd (all $ps < .01$) and no other differences between any of the 4 peaks were observed.

The word recognition data for each of the five adaptation conditions (control, 1, 2, 4, 8 cpd) are shown in Figure 3. A one-way repeated measures ANOVA showed a significant effect of adaptation condition [$F(4,76) = 15.76, p < .001$]. Tukey tests confirmed the pattern of effects apparent in Figure 3; all adaptation frequencies produced a drop in performance relative to the control condition (all $ps < .01$), although 4 cpd produced the biggest drop, and this was significantly greater than for all other frequencies (all $ps < .01$). No other differences were significant.

DISCUSSION

These findings provide an important indication of the effects of spatial frequency adaptation on word recognition. From the results obtained, adaptation to all of the adapta-

Figure 2. Mean sensitivity decrease (log units) produced by each of the four adaptation stimuli (1, 2, 4, 8 cpd) for each test frequency in the preliminary assessment task. Each decrease is the difference in contrast sensitivity between using the nonadaptation control and each adaptation stimulus.

tion frequencies used in the experiment (1, 2, 4, and 8 cpd) impaired word recognition, although the maximum impairment was produced by adapting to 4 cpd. However, the results of the adaptation assessment procedure indicate that the word recognition impairment observed for each adaptation frequency was not a simple product of the spatial frequency suppression produced by each adaptation frequency. In particular, similar levels of spatial frequency suppression were observed after adapting to 4 and 8 cpd, but adapting to 4 cpd produced the greater effect on word recognition. Moreover, the effects on word recognition involved the suppression of sensitivity not only to the adaptation frequencies used but also to frequencies adjacent to these center frequencies, indicating support for the view that identifying the role of spatial frequencies in word recognition requires information on how clusters of spatial frequencies, rather

than only individual frequencies, contribute to this process (e.g., Pelli et al., 2003). Indeed, the effects observed indicate that word recognition involves a range of spatial frequencies, corresponding, by virtue of the number of letters per degree (4) and the width of words (1.5°) used in this particular experiment, to cues to individual letters, groups of letters, and even the overall horizontal extent of words.

The finding that a combination of frequencies contributes to word perception concurs with the findings of previous studies that have used band-pass-filtered images of words (e.g., Leat & Munger, 1994; Patching & Jordan, 2005), and adds support to the view that word perception operates over a range of spatial scales. However, differences with this previous work were observed. For example, the findings of Patching and Jordan (2005) suggest that word recognition is barely better than chance when images contain only

Figure 3. Mean word recognition performance (% correct) for each adaptation condition in the experiment.

frequencies of around 1 cpd, whereas the findings obtained using adaptation suggest that these low spatial frequencies are important in word perception. Thus, whereas filtered images in which only low spatial frequencies are present may simply be too difficult to process, adaptation allows a more sensitive assessment of spatial frequency involvement in word perception. However, the greatest contrast between the findings reported here and previous findings is with studies in which word stimuli have been embedded in visual noise, which suggest that the role of spatial frequencies in word perception is confined to perception of individual letters (e.g., Majaj et al., 2003; Pelli et al., 2003). Conceivably, attempting to extract the identity of a word from a background of obvious visual noise inspires deliberate (and unusual) strategies of perception, and one such strategy may be letter-by-letter reading. Thus, when no visible noise is apparent (e.g., when adaptation is used), the overarching role of individual letter perception in word perception disappears. Further research will no doubt unravel these issues.

This study is presented as a first glimpse at the effects of adaptation on word recognition, and further work is now required to delineate these effects fully. However, the major purpose of the findings presented is to indicate the viability of the adaptation technique for studying the role of spatial-frequency-dependent processes in word recognition. Clear effects of adaptation on word recognition performance were observed, and further experimentation, using other adaptation frequencies and levels of adaptation to manipulate the suppression of different frequencies, will provide progressive clarification of the spatial frequencies underpinning word recognition using an experimental effect that is "invisible" to participants. Moreover, this study has applied the technique to just single-word perception, but more complex reading situations can be investigated in much the same way, including delineating the role of different spatial frequencies in processing whole sentences and pages of text. Indeed, altering the spatial frequency sensitivity of observers rather than altering the spatial frequency content of stimuli provides a highly adaptable method of studying perception of a variety of linguistic stimuli without the need for complex changes to the spatial frequency content of the actual target stimuli used.

AUTHOR NOTE

The research described in this article was supported by Wellcome Trust Grant 059727 to T.R.J. We thank David Omtzigt for assistance in the production of this article. Correspondence concerning this article should be addressed to T. R. Jordan, School of Psychology, Faculty of Medicine and Biological Sciences, Henry Wellcome Building, University of Leicester, Leicester LE1 9HN, England (e-mail: prof.timjordan@leicester.ac.uk).

REFERENCES

- ALLEN, P. A., STADTLANDER, L. M., GROTH, K. E., PICKLE, J. L., & MADDEN, D. J. (2000). Adult age invariance in sentence unitization. *Aging Neuropsychology & Cognition*, *7*, 54-67.
- ALLEN, P. A., WALLACE, B., & WEBER, T. A. (1995). Influence of case type, word frequency, and exposure duration on visual word recognition. *Journal of Experimental Psychology: Human Perception & Performance*, *21*, 914-934.
- BACCUS, S. A., & MEISTER, M. (2002). Fast and slow contrast adaptation in retinal circuitry. *Neuron*, *36*, 909-919.
- BACCUS, S. A., & MEISTER, M. (2004). Retina versus cortex: Contrast adaptation in parallel visual pathways. *Neuron*, *42*, 5-7.
- BAILEY, I. L., & LOVIE, J. E. (1976). New design principles for visual-acuity letter charts. *American Journal of Optometry & Physiological Optics*, *53*, 740-745.
- BALOTA, D. A., CORTESE, M. J., SERGENT-MARSHALL, S. D., SPIELER, D. H., & YAP, M. J. (2004). Visual word recognition of single-syllable words. *Journal of Experimental Psychology: General*, *133*, 283-316.
- BARBER, H., VERGARA, M., & CARREIRAS, M. (2004). Syllable-frequency effects in visual word recognition: Evidence from ERPs. *NeuroReport*, *15*, 545-548.
- BLAKEMORE, C., & CAMPBELL, F. W. (1969). On the existence of neurones in the human visual system selectively sensitive to the orientation and size of retinal images. *Journal of Physiology*, *203*, 237-260.
- BLAKEMORE, C., MUNCEY, J. P. J., & RIDLEY, R. M. (1973). Stimulus specificity in the human visual system. *Vision Research*, *13*, 1915-1931.
- BODINGER, D. M. (1978). The decay of grating adaptation. *Vision Research*, *18*, 89-91.
- BOROWSKY, R., & BESNER, D. (1993). Visual word recognition: A multi-stage activation model. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *19*, 813-840.
- BOYNTON, G. M., & FINNEY, E. M. (2003). Orientation-specific adaptation in human visual cortex. *Journal of Neuroscience*, *23*, 8781-8787.
- BRAINARD, D. H. (1997). The Psychophysics Toolbox. *Spatial Vision*, *10*, 433-436.
- CATTELL, J. M. (1885). Über die Zeit der Erkennung und Benennung von Schriftzeichen, Bildern, und Farben. *Philosophische Studien*, *2*, 635-650.
- CHUNG, S., LEVI, D., & TJAN, B. (2003). Channel for letter identification is unaffected by spatial-frequency adaptation [Abstract]. *Optometry & Vision Science*, *80*(Suppl.) 24.
- COLTHEART, M., RASTLE, K., PERRY, C., LANGDON, R., & ZIEGLER, J. (2001). DRC: A dual route cascaded model of visual word recognition and reading aloud. *Psychological Review*, *108*, 204-256.
- DE VALOIS, K. K. (1977). Spatial-frequency adaptation can enhance contrast sensitivity. *Vision Research*, *17*, 1057-1065.
- FOLEY, J. M., & BOYNTON, G. M. (1993). Forward pattern masking and adaptation: Effects of duration, interstimulus interval, contrast, and spatial and temporal frequency. *Vision Research*, *33*, 959-980.
- FORSTER, K. I., & VERES, C. (1998). The prime lexicality effect: Form-priming as a function of prime awareness, lexical status, and discrimination difficulty. *Journal of Experimental Psychology: Learning, Memory, & Cognition*, *24*, 498-514.
- GARDNER, J. L., SUN, P., WAGGONER, R. A., UENO, K., TANAKA, K., & CHENG, K. (2005). Contrast adaptation and representation in human early visual cortex. *Neuron*, *47*, 607-620.
- GEORGESON, M. A., & GEORGESON, J. M. (1987). Facilitation and masking of briefly presented gratings: Time-course and contrast dependence. *Vision Research*, *27*, 369-379.
- GINSBURG, A. P. (1980). Specifying relevant spatial information for image evaluation and display design: An explanation of how we see certain objects. *Proceedings of the Society for Information Display*, *21*, 219-227.
- GINSBURG, A. P. (1986). Spatial filtering and visual form perception. In K. R. Boff, L. Kaufman, & J. P. Thomas (Eds.), *Handbook of perception and human performance* (Vol. 2, chap. 34, pp. 1-41). New York: Wiley.
- GRAINGER, J., BOUTTEVIN, S., TRUC, C., BASTIEN, M., & ZIEGLER, J. (2003). Word superiority, pseudoword superiority, and learning to read: A comparison of dyslexic and normal readers. *Brain & Language*, *87*, 432-440.
- GRAINGER, J., & JACOBS, A. M. (1996). Orthographic processing in visual word recognition: A multiple read-out model. *Psychological Review*, *103*, 518-565.
- GREENLEE, M. W., GEORGESON, M. A., MAGNUSSEN, S., & HARRIS, J. P. (1991). The time course of adaptation to spatial contrast. *Vision Research*, *31*, 223-236.
- GREENLEE, M. W., & HEITGER, F. (1988). The functional role of contrast adaptation. *Vision Research*, *28*, 791-797.
- GROSS, J., TREIMAN, R., & INMAN, J. (2000). The role of phonology in a letter detection task. *Memory & Cognition*, *28*, 349-357.

- HEALY, A. F. (1994). Letter detection: A window to unitization and other cognitive processes. *Psychonomic Bulletin & Review*, **1**, 333-344.
- HEGGLUND, P., & HOHMANN, A. (1976). Long-term retention of the "Gilinsky-effect." *Vision Research*, **16**, 1015-1017.
- HEINRICH, T. S., & BACH, M. (2002). Contrast adaptation in retinal and cortical evoked potentials: No adaptation to low spatial frequencies. *Visual Neuroscience*, **19**, 645-650.
- HOOPER, D. A., & PAAP, K. R. (1997). The use of assembled phonology during performance of a letter recognition task and its dependence on the presence and proportion of word stimuli. *Journal of Memory & Language*, **37**, 167-189.
- JONES, R. M., & TULUNAY-KEESEY, U. (1975). Local retinal adaptation and spatial frequency channels. *Vision Research*, **15**, 1239-1244.
- JORDAN, T. R. (1986). Testing the BOSS hypothesis: Evidence for position-insensitive orthographic priming in the lexical decision task. *Memory & Cognition*, **14**, 523-532.
- JORDAN, T. R. (1990). Presenting words without interior letters: Superiority over single letters and influence of postmask boundaries. *Journal of Experimental Psychology: Human Perception & Performance*, **16**, 893-909.
- JORDAN, T. R. (1995). Perceiving exterior letters of words: Differential influences of letter fragment and non-letter fragment masks. *Journal of Experimental Psychology: Human Perception & Performance*, **21**, 512-530.
- JORDAN, T. R., & BEVAN, K. M. (1996). Position-specific masking and the word-letter phenomenon: Re-examining the evidence from the Reicher-Wheeler paradigm. *Journal of Experimental Psychology: Human Perception & Performance*, **22**, 1416-1433.
- JORDAN, T. R., & PATCHING, G. R. (2006). Assessing effects of fixation demands on perception of lateralized words: A visual window technique for studying hemispheric asymmetry. *Neuropsychologia*, **44**, 686-692.
- JORDAN, T. R., PATCHING, G. R., & MILNER, A. D. (1998). Central fixations are inadequately controlled by instructions alone: Implications for studying cerebral asymmetry. *Quarterly Journal of Experimental Psychology*, **51A**, 371-391.
- JORDAN, T. R., PATCHING, G. R., & THOMAS, S. M. (2003a). Assessing the role of hemispheric specialization, serial-position processing and retinal eccentricity in lateralized word perception. *Cognitive Neuropsychology*, **20**, 49-71.
- JORDAN, T. R., PATCHING, G. R., & THOMAS, S. M. (2003b). Asymmetries and eccentricities in studies of lateralized word recognition: A response to Nazir. *Cognitive Neuropsychology*, **20**, 81-89.
- JORDAN, T. R., THOMAS, S. M., & SCOTT-BROWN, K. C. (1999). The illusory letters phenomenon: An illustration of graphemic restoration in visual word recognition. *Perception*, **28**, 1413-1416.
- KEYSERS, C., & PERRETT, D. I. (2002). Visual masking and RSVP reveal neural competition. *Trends in Cognitive Sciences*, **6**, 120-125.
- LEAT, S. J., & MUNGER, R. (1994). A new application of band-pass fast Fourier transforms to the study of reading performance. *Technical Digest Series: Optical Society of America*, **2**, 250-253.
- LUNN, R., & BANKS, W. P. (1986). Visual fatigue and spatial frequency adaptation to video displays of text. *Human Factors*, **28**, 457-464.
- MAGNUSSEN, S., DYRNES, S., GREENLEE, M. W., NORDBY, K., & WATTEN, R. (1992). Time course of contrast adaptation to VDU-displayed text. *Behaviour & Information Technology*, **11**, 334-337.
- MAGNUSSEN, S., & GREENLEE, M. W. (1985). Marathon adaptation to spatial contrast: Saturation in sight. *Vision Research*, **25**, 1409-1411.
- MAJAJ, N. J., LIANG, Y. X., MARTELLI, M., BERGER, T. D., & PELLI, D. G. (2003). Channel for reading [Abstract]. *Journal of Vision*, **3**, 813a.
- MARRIOTT, F. H. C. (1965). Thresholds for negative after-images. *Journal of Physiology*, **180**, 888-892.
- MAYALL, K., HUMPHREYS, G. W., MECHELLI, A., OLSON, A., & PRICE, C. J. (2001). The effects of case mixing on word recognition: Evidence from a PET study. *Journal of Cognitive Neuroscience*, **13**, 844-853.
- MCCLELLAND, J. L., & RUMELHART, D. E. (1981). An interactive activation model of context effects in letter perception: Part 1. An account of basic findings. *Psychological Review*, **88**, 375-407.
- MECACCI, L., & SPINELLI, D. (1976). The effects of spatial frequency adaptation on human evoked potentials. *Vision Research*, **16**, 477-479.
- MIKAEILIAN, H. H. (1988). Changes in contrast sensitivity function produced by VDT use. *International Journal of Man-Machine Studies*, **28**, 637-642.
- PAAP, K. R., NEWSOME, S. L., McDONALD, J. E., & SCHVANEVELDT, R. W. (1982). An activation verification model for letter and word recognition: The word superiority effect. *Psychological Review*, **89**, 573-594.
- PATCHING, G. R., & JORDAN, T. R. (2005). Assessing the role of different spatial frequencies in word perception by good and poor readers. *Memory & Cognition*, **33**, 961-971.
- PELLI, D. G. (1989). Reading and contrast adaptation. *Technical Digest Series: Optical Society of America*, **16**, 102-103.
- PELLI, D. G. (1997). The VideoToolbox software for visual psychophysics: Transforming numbers into movies. *Spatial Vision*, **10**, 437-442.
- PELLI, D. G., & FARELL, B. (1994). Psychophysical methods. In M. Bass, E. W. Van Stryland, D. R. Williams, & W. L. Wolfe (Eds.), *Handbook of optics* (2nd ed.). New York: McGraw-Hill.
- PELLI, D. G., FARELL, B., & MOORE, D. C. (2003). The remarkable inefficiency of word recognition. *Nature*, **423**, 752-756.
- PEREA, M., & LUPKER, S. J. (2004). Can CANISO activate CASINO? Transposed-letter similarity effects with nonadjacent letter positions. *Journal of Memory & Language*, **51**, 231-246.
- RASTLE, K., & COLHEART, M. (1999). Lexical and nonlexical phonological priming in reading aloud. *Journal of Experimental Psychology: Human Perception & Performance*, **25**, 461-481.
- REICHER, G. M. (1969). Perceptual recognition as a function of meaningfulness of stimulus material. *Journal of Experimental Psychology*, **81**, 275-280.
- ROSE, D., & EVANS, R. (1983). Evidence against saturation of contrast adaptation in the human visual system. *Perception & Psychophysics*, **34**, 158-160.
- ROSE, D., & LOWE, I. (1982). Dynamics of adaptation to contrast. *Perception*, **11**, 505-528.
- SMITH, R. A., JR. (1977). Spatial-frequency adaptation and afterimages. *Perception*, **6**, 153-160.
- SNOWDEN, R. J. (1994). Adaptability of the visual system is inversely related to its sensitivity. *Journal of the Optical Society of America A*, **11**, 25-32.
- SOLOMON, S. G., PEIRCE, J. W., DHURV, N. T., & LENNIE, P. (2004). Profound contrast adaptation early in the visual pathway. *Neuron*, **42**, 155-162.
- SUTER, S., ARMSTRONG, C. A., SUTER, P. S., & POWERS, J. C. (1991). Spatial-frequency-tuned attenuation and enhancement of the steady-state VEP by grating adaptation. *Vision Research*, **31**, 1167-1175.
- WATSON, A. B., & PELLI, D. G. (1983). QUEST: A Bayesian adaptive psychometric method. *Perception & Psychophysics*, **33**, 113-120.
- WATSON, A. B., & ROBSON, J. G. (1981). Discrimination at threshold: Labelled detectors in human vision. *Vision Research*, **21**, 1115-1122.
- WHEELER, D. D. (1970). Processes in word recognition. *Cognitive Psychology*, **1**, 59-85.

NOTES

1. On the one hand, the onset of the target should be presented sufficiently close to the offset of the adaptation stimulus so as to maximize the effect of adaptation. On the other hand, having the target too close to adaptation offset may make it difficult to determine whether any effects obtained are due to adaptation or to forward masking. However, it should be noted that forward masking and adaptation may actually be similar phenomena (e.g., Foley & Boynton, 1993; Georgeson & Georgeson, 1987).

2. Evidence indicates that spatial frequency adaptation is orientation specific (for a recent study, see Boynton & Finney, 2003). Consequently, vertical gratings can be used to disrupt perception of the horizontal components of words (e.g., width) but gratings of other orientations (e.g., horizontal) can be used to investigate other aspects of stimulus processing (e.g., height).