Enhanced Motion Aftereffects in Migraine Are Related to Contrast Sensitivity: Implications for Models of Differences in Precortical/Cortical Function

Pia Singh and Alex J. Shepherd

Department of Psychological Sciences, Birkbeck, University of London, London, United Kingdom

Correspondence: Alex J. Shepherd, Department of Psychological Sciences, Birkbeck, University of London, Malet Street, London, WC1E 7HX, UK;
a.shepherd@bbk.ac.uk.

Submitted: July 13, 2015
Accepted: February 5, 2016

Citation: Singh P, Shepherd AJ. Enhanced motion aftereffects in migraine are related to contrast sensitivity: implications for models of differences in precortical/cortical function. *Invest Ophthalmol Vis Sci*. 2016;57:1228–1234. DOI:10.1167/iovs.15-17692

Purpose. Visual tests can be used as noninvasive tools to test models of the pathophysiology underlying neurological conditions, such as migraine. For example, there are reports that the motion aftereffect, which involves neural processing in several cortical areas, is prolonged in migraine. There also are reports of impaired contrast sensitivity in migraine, however, attributed to a precortical dysfunction. This study explored associations between these two tests of visual function. Specifically, it aimed to clarify whether the magnitude of the motion aftereffect is affected by contrast and contrast sensitivity.

Methods. The motion aftereffect was elicited after observers viewed a coherently moving pattern for 45 seconds. The duration of the subsequent aftereffect was measured with three different test display contrasts (high, medium, low). Contrast sensitivity also was assessed.

Results. For each test display contrast, the motion aftereffect was prolonged in migraine compared to the control group. Contrast sensitivity was poorer in the migraine group and was a significant predictor of motion aftereffect duration.

Conclusions. These results suggest an anomaly in early motion processing pathways in migraine that likely is linked with those pathways underlying contrast sensitivity. They provide further evidence for differences in visual processing that begin early, potentially starting at the retina, which have consequences for performance on tasks that putatively examine cortical processing. Differences in precortical and cortical visual pathways are implicated in the pathophysiology underlying migraine.

Keywords: migraine, motion perception, contrast sensitivity, visual processing, cortical processing, motion aftereffect

Migraine is a common neurological condition estimated to affect more than 10% of the world's population at any given time, and women are three times more likely to be affected than men.[1,2] The pathophysiology of migraine still is not entirely understood. Much research has paid attention to visual processing in migraine due to the intense sensitivity to light (photophobia) that patients can experience during a migraine, the visual disturbances that may precede or accompany an attack (the visual aura), and the fact that visual stimuli can trigger attacks.[3–9] The perception of motion has been a particular focus and this study continues in this vein. Psychophysical studies using various visual motion-processing paradigms (e.g., pattern adaptation, threshold discrimination, and threshold detection) have revealed differences in performance between migraine and control groups. Generally, the migraine group's performance is impaired.[10–15] Although different researchers often propose different models of anomaly in the visual system, there is a general consensus that abnormal cortical processing is an underlying factor in the pathophysiology of migraine and underlies these group differences in motion perception.

The experimental paradigm used here is one that has been used recently in migraine research: the motion aftereffect (MAE).[10,13] The MAE can be seen after prolonged exposure to coherent motion in a particular direction. Once the motion stops, any subsequently presented display appears to drift in the opposite direction. The MAE has been used extensively in basic vision research and has contributed significantly to the mapping of motion selective pathways in the visual system. It is a visual illusion that offers a noninvasive and simple opportunity to assess activity attributed to processing in the visual cortex.[10,13,16] One clear indication that the MAE involves cortical activity is its ability to transfer interocularly: that is, if the adapting display is viewed with one eye only, but the test display is presented to the other eye, the illusion still is seen, although it may be at a weaker intensity.[16,17] Binocular cells, which are activated by displays presented to either eye, are found first in abundance in the primary (striate/V1) visual cortex.[18,19]

The MAE is produced by a biased distribution of activity in direction-selective neurons in the visual system.[20] Direction-selective neurons, like any other cortical neurons, produce a steady low-level of spontaneous activity when not engaged by any stimulus. If a visual display contains elements with a certain motion direction and speed that activates particular neurons, their initially rapid firing rate will decline steadily for as long as the stimulus is present, that is, the cells get adapted. When the motion stops, the neurons take a little while to "recover" and regain normal levels of spontaneous activity. During that time, the spontaneous activity of all other neurons sensitive to

different motion directions exceeds that of the suppressed neurons. This produces a biased distribution of spontaneous activity that is similar to activity produced by slow motion in the opposite direction, and that results in the perceived aftereffect.[21,22]

To explore differences in cortical processing between people with and without migraine, Shepherd[10,13] studied the magnitude of the MAE, measured as the duration of the illusory motion, and found that the MAE was more pronounced in migraine, that is, it lasted longer than in the control group. Often, the MAE is examined using drifting sine-wave gratings for adapting displays, and stationary or counter-phasing sine-wave gratings as test displays. Shepherd,[10,13] however, instead used random dot displays for adapting and test displays. Group differences that may arise with gratings are likely to confound differences in motion perception with differences in the perception of gratings, likely since gratings can induce visual discomfort, which is more pronounced in migraine (reviewed previously[7]). The classic motion aftereffect with random dot displays involves stationary test displays, which yields a local motion aftereffect where the test display appears to drift, yet the dots that comprise the display do not appear to change position. When the test display is itself dynamic (which, with random dots, appears like a detuned television), illusory motion is seen again but this time the motion looks like real motion. It is described as a global motion percept. Shepherd[10,13] used stationary and dynamically twinkling random dot test displays that were presented either immediately after the adapting motion stopped, or after a 15-second delay, to compare the phenomenon of storage of the MAE in migraine and control groups. The global MAE stored almost completely over a 15-second delay, whereas the local MAE stored only partially. Because of these differences in appearance and storage, local and global MAEs have been interpreted as showing adaptation at different stages within the visual pathways.

Shepherd,[7,13] therefore, discussed general models or descriptions of the motion aftereffect, as proposed by early researchers, such as Sutherland[21] and Barlow and Hill,[23] in the context of more recent models that have tried to anchor elements of the illusory aftereffect to particular stages of processing within the visual pathways (see prior reports[7,10,13,14]). The conclusion was that multiple sites are involved in adaptation to motion, which can be tapped with careful selection of adapting and test displays.[13] Extrinsic factors (such as context and synaptic efficacy between populations of neurons tuned to various attributes of the adapting and test displays) and intrinsic factors (such as fatigue-like processes/membrane hyperpolarization) can be addressed with particular paradigms.

Shepherd[10,13] proposed that the enhanced MAEs were the result of slow cellular recovery and/or an extended suppression of cortical excitatory synaptic connections between cells that responded to the adapting display. It was concluded, by using the different types of adapting and test displays (stationary or dynamic/twinkling test displays), that cortical processing at early (V1/striate cortex) and later (V5/MT) visual areas sensitive to motion were affected in migraine. Earlier levels of cortical motion processing were assessed with the stationary test displays; early and later levels with the dynamic or twinkling test displays.[10,13,16,17,24,25] No significant differences were found between migraine groups with and without visual aura. Here, the MAE duration was assessed for static displays presented immediately after the adapting motion ceased, thereby involving processes involving changes in synaptic efficacy and cellular recovery.[13]

In this study, the effects of contrast and contrast sensitivity on the MAE in migraine and control groups were explored. Direction-selective cells in early motion processing pathways in the striate cortex (V1) are affected by contrast as well as motion. An early study by Keck et al.[26] investigated the effect of adapting and test display contrasts using drifting sinusoidal gratings as adapting displays, and stationary sinusoidal gratings as test displays. Whether the participants included people with migraine is likely but is not known. Despite this caveat, it is relevant to the present study. They reported that the magnitude of the MAE increased with increasing adaptation contrast or with decreasing test display contrast, that is, it was maximal for high contrast adapting gratings paired with low contrast test displays. As described above, the MAE occurs due to a biased distribution of spontaneous activity in direction-selective cells. Prolonged MAEs for low contrast test displays can occur if the residual firing rate of adapted cells in response to high contrast test displays is stronger than that to the low contrast test displays, while the firing rates of unadapted cells remain higher in both conditions. Thus, the imbalance in activity between adapted and unadapted cells would be greater for low contrast test displays than for high, which results in a longer MAE for the low contrast test displays.

There have been consistent reports of impaired contrast sensitivity in migraine. Such results have been attributed to abnormal precortical processing.[14,27–30] Input to higher order cortical centers relies on the adequate processing of information in precortical pathways. Therefore, contrast sensitivity differences between migraine and nonheadache control groups resulting from precortical abnormalities could result in reduced input to cortical centers. Consequently, differences in early visual processing may have consequences that could be misattributed to differences in cortical processing. Shepherd et al.[14] included contrast and contrast sensitivity in a relative motion, global motion detection, and global motion discrimination study in migraine. They reported their migraine group had significantly poorer contrast sensitivity, that is, they had higher contrast thresholds, than the control group. Contrast sensitivity also correlated significantly with performance on each motion task. As expected from previous work, these correlations showed that poorer contrast sensitivity was associated with fewer correct responses on a motion direction detection task and poorer performance (higher thresholds) on global and relative motion discrimination tasks. When contrast sensitivity was added as a covariate to the analyses, however, the group differences disappeared for the motion direction detection thresholds and relative motion tasks. For their motion discrimination task, the group differences persisted, however, so it was concluded that there are cortical variations in migraine, in addition to impaired contrast sensitivity, and that anomalous processing in low-level (precortical) pathways can confound interpretation of performance on other tasks if not taken into account.

The aim of the current experiment was to assess whether the MAE is affected by contrast and contrast sensitivity in migraine and control groups. As described above, MAEs can be seen in test displays that are either stationary, or that also display temporal modulation. Here, the MAE duration was assessed in stationary test displays as the perceived aftereffect in such displays has been attributed to earlier stages of visual processing and, therefore, may be the more likely to show effects of contrast sensitivity, which also has been attributed to precortical visual processing.[28]

Trials consisted of three different test display contrasts (high, medium, and low). The adaptation contrast was kept constant (medium). The migraine group was predicted to have longer duration MAEs than the control group across all test contrast conditions.[10,13] Larger effects were predicted for low compared to high contrast test displays in both groups.[26]

Poorer contrast sensitivity was predicted in the migraine group.[14,27–30] By including contrast sensitivity in the analyses of the MAE data, this study aimed to determine any contribution of reduced contrast sensitivity to prolonged MAEs or whether any anomaly in early motion processing pathways (e.g.. up to and including V1) is independent of contrast sensitivity. Finally, no distinction was made between migraine participants with and without aura. This was decided due to previous research that has consistently failed to find significant differences between these subgroups in the magnitude of the MAE, nor in other motion tasks.[10,13–15]

Method

Participants

Each participant completed either a migraine or a headache questionnaire that detailed the characteristics of their migraine/headache symptoms, their frequency, and duration. All in the migraine group fulfilled the International Headache Society (IHS) criteria for migraine.[31] None in the control group experienced regular or severe headaches that fulfilled IHS criteria. Of the control participants who reported having headaches, they were tension-type, sinus-related, or due to dehydration. All testing was performed when participants appeared symptom-free and none had experienced a migraine/headache for 48 hours on either side of the test session. None of the participants was on prophylactic medication for any condition, nor had they taken any acute medication within 48 hours of the test session. All participants had a binocular visual acuity of at least 20/25, with or without optometric correction.

We initially recruited 20 migraine participants; however, eight were excluded as they either reported having a migraine within 48 hours of the test session, or they failed to meet the IHS criteria.[31] Thus, 12 migraine participants were tested (11 female, 1 male; age, 32.0 ± 9.9 years; range, 20–54; 6 with visual aura) and they were approximately age-matched to 12 control participants (7 female, 5 male; age, 32.6 ± 6.9 years; range, 20–47). Participants were recruited from advertisements and an existing migraine database at Birkbeck College (London, United Kingdom). They received either course credit or a small honorarium for their participation.

The study received ethical approval from Birkbeck's Department of Psychological Sciences Ethical Committee. Informed written consent was obtained from all participants in accordance with the Declaration of Helsinki (1991).

Apparatus/Materials

Motion Aftereffect (MAE). The displays were created using experimental scripts developed in C in conjunction with routines from the Video Toolbox.[32] The stimuli were presented on a 21-inch CRT monitor (LaCie, Paris, France) connected to an Apple Macintosh G4 computer (Apple, Cupertino, CA, USA). The CRT monitor had a spatial and temporal resolution of 1280 × 960 pixels, and 100 Hz, respectively. Trials consisted of an adapting and test display that, together, elicited the MAE.

Adapting Display. A 14° square window displayed random light and mid-grey pixels (average luminance = 30 cdm^{-2}, Michelson contrast = 30%) moving coherently upwards at a speed of 3°/s. The adapting display was presented for 45 seconds. Participants were seated 60 cm from the monitor in an otherwise dark room. During presentation of the adapting displays, participants were asked to look at a fixation point at the center of the screen while paying attention to the whole display. The experiment consisted of 12 trials, divided into the three blocks, one for each of the test display contrasts (the contrast of the adapting display was always the same). Block order was randomized. Thus, the experiment had a mixed quasi-experimental design, with contrast as the within-subjects factor and group as the between. The experiment was preceded by six practice trials (two for each test display contrast).

Test Displays. Immediately after adaptation, participants were presented with a test display. Test displays contained random, stationary, light to dark-grey pixels, which resembled that of a snapshot taken of a detuned television. Three different contrast test displays were used – high (Michelson contrast 78%), medium (30%), and low (0.1%). All test displays had the same mean luminance as the adapting display (30 cdm^{-2}). The presentation of a test display immediately after the adapting display elicited the illusion of slow, downward motion. When the stationary test display appeared, participants were asked to try not to blink and to indicate when the illusory motion stopped by pressing a key on the computer keyboard. The experimental session lasted between 75 and 90 minutes. Participants initiated each trial with a keypress and so could sit quietly between trials, in the darkened room, if they wished to pause or take a break. An experimenter was present throughout the experimental session. As part of the consent, participants were informed they could withdraw at any time without penalty, but none did so.

Contrast Sensitivity. The Cambridge Low Contrast Gratings (CLCG) measure contrast sensitivity at a spatial frequency of 4 cycles per degree, close to the maximum sensitivity of the human visual system. It consists of 10 horizontally oriented square wave gratings viewed at a distance of 6 meters. Each grating is presented together with a blank page that has the same mean reflectance as its grating pair. The participants' task is simply to indicate which page, top or bottom, contains the grating. The gratings decrease in Michelson contrast on subsequent trials through a range of 13% to 0.14%. The test was completed in order of decreasing contrast. Each time an error was made, the sequence was restarted at three plates preceding the error. The plates where errors were made were recorded on three runs through the sequence. Contrast sensitivity was measured before the MAE.

Results

The MAE and CLCG data from each group were normally distributed (Kolmogorov-Smirnov tests, $P > 0.05$), so group differences were assessed with ANOVA, *t*-tests, Pearson's correlation coefficient and analysis of covariance (ANCOVA) using PASW statistics version 20 (SPSS Inc., Chicago, IL, USA). Mauchly's test of sphericity was met for the ANOVA and ANCOVA ($P > 0.15$).

Average MAE durations for each group in each condition are shown in Figure 1A. Several trends are clear. Overall, the MAE lasted longer in the migraine group than in the control group for all three test display contrasts. Second, high contrast test displays produced the shortest MAEs and low contrasts the longest, as expected.[26] This was the same for both groups; however, the trend was more pronounced in the migraine group. A 2 (group) × 3 (test display contrast) mixed ANOVA was first performed on these data. The group *x* contrast interaction was significant ($F[2,44] = 4.9$, $P = 0.01$, $\eta_p^2 = 0.18$, $\omega_p^2 = 0.142$), confirming that the increase in MAE duration with decreasing test display contrast, was greater in the migraine group. Three planned comparisons revealed that the MAE durations for the high and medium contrast test

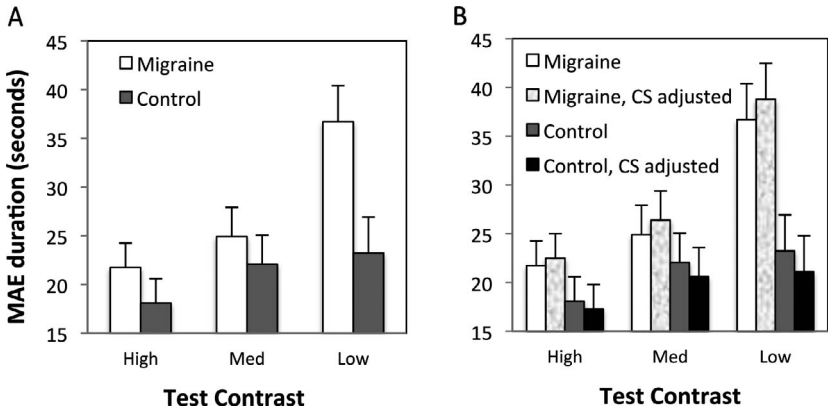

FIGURE 1. Motion aftereffect (MAE) data. (**A**) Means (+1 SE) of the MAE duration for the migraine and control groups for high, medium, and low contrast test displays. (**B**) Same data adjusted for the effect of the covariate, CLCG contrast sensitivity. For each test display contrast, the MAE duration is increased slightly for the migraine group, but decreased for the control group, when adjusted for contrast sensitivity.

displays did not differ significantly between the migraine and control groups ($t[22] = 1.0$, $P = 0.15$; $t[22] = 0.6$, $P = 0.26$; respectively, 1-tailed), but the MAE durations for the low contrast test display did ($t[22] = 2.4$, $P = 0.013$, 1-tailed). This interaction was associated with a significant main effect of contrast, confirming that the MAE duration, for both groups, increased as the test display contrast decreased ($F[2,44] = 14.4$, $P < 0.001$, $\eta_p^2 = 0.40$, $\omega_p^2 = 0.363$). There was no significant main effect of group ($F[1,22] = 2.7$, $P = 0.12$, $\eta_p^2 = 0.11$, $\omega_p^2 = 0.066$).

Scores on the CLCG were converted into Michelson contrast. Higher contrast thresholds equal poorer contrast sensitivity, that is, people needing a higher contrast to identify the gratings. Consistent with previous reports, the migraine group had higher contrast thresholds than the control group (mean ± 1 SE; migraine, 0.38 ± 0.08; control, 0.26 ± 0.03). Nevertheless, the difference was not statistically significant ($t[22] = 1.6$, $P = 0.065$, 1-tailed).

Correlations between each condition on the MAE tests and CLCG produced no significant results in the control group (high contrast test display, $r = -0.15$, $P = 0.64$; medium contrast $r = -0.29$, $P = 0.36$; low contrast $r = -0.17$, $P = 0.60$, Pearson's r, 2-tailed; Fig. 2B). In the migraine group, the MAE and CLCG correlations nearly reached significance for the low contrast test displays only (high contrast, $r = -0.33$, $P = 0.30$; medium contrast, $r = -0.49$, $P = 0.16$; low contrast, $r = -0.51$, $P = 0.088$, 2-tailed; Fig. 2A). Although failing to reach statistical significance, these consistently negative correlations show a trend that poorer contrast sensitivity (i.e., needing a higher contrast to identify the gratings) was associated with shorter MAEs, particularly for the low contrast test displays in the migraine group. The r^2 values indicate that, in the migraine group, between 11% and 26% of the variability in MAE duration was predictable from the variability in contrast sensitivity as assessed by the CLCG, but, in the control group, only between 2% and 9% of the variability in MAE duration was predictable from their variability in contrast sensitivity.

Contrast sensitivity may have had an effect on the MAE in the migraine group despite the nonsignificant group differences and correlations. Therefore, CLCG contrast sensitivity was added as a covariate and the ANOVA repeated as an ANCOVA in a second analysis. Because the analysis included repeated-measures, CLCG contrast sensitivity scores were first mean centered as recommended by Delaney and Maxwell[33]: the mean of all participants was subtracted from individual scores. The relationship between these adjusted contrast scores and MAE duration for each test display contrast did not differ between the groups, indicating that the assumption of homogeneity of regression slopes was met (three univariate ANOVAs, one for each test display contrast, all Fs < 1). The ANCOVA revealed that contrast sensitivity significantly predicted performance on the MAE ($F[1,21] = 5.6$, $P = 0.03$,$\eta_p^2 = 0.21$, see Fig. 1B). Again, the significant group x contrast interaction ($F[2,42] = 6.7$, $P = 0.003$, $\eta_p^2 = 0.24$) reflected that the increase in MAE duration with decreasing test display contrast was greater in the migraine than in the control group (see Fig. 1B). This time this interaction was related to two significant main effects. With contrast sensitivity as a covariate, the main effect of group was significant, indicating that the migraine group had significantly longer MAEs than the control group regardless of test display contrast ($F[1,21] = 6.0$, $P = 0.023$, $\eta_p^2 = 0.22$). As in the previous analysis, the main effect of test display contrast confirmed that the MAE lasted longer for low contrast test displays than for high for both groups ($F[2,42] = 15.5$, $P < 0.001$, $\eta_p^2 = 0.42$). The interaction between contrast sensitivity and test display contrast was not significant ($F[2,42] = 2.6$, $P = 0.09$, $\eta_p^2 = 0.11$).

DISCUSSION

The rationale for the current experiment was based on previous research that has reported longer MAEs in migraine and other research showing impaired contrast sensitivity.[10,13,14,30] In line with the predictions, the MAE in the migraine group lasted longer than in the control group and low contrast test displays produced the longest MAEs in both groups. Significant group and interaction effects confirmed this; however, the significant group difference was only found in the second analysis (ANCOVA) when contrast sensitivity was added as a covariate. Contrary to previous research,[14,27,29,30] and to what had been predicted, there was no statistically significant difference between the control and migraine groups in contrast sensitivity. There was, nevertheless, a trend for the migraine group to have higher contrast thresholds, that is, they needed higher contrasts to be able to see the gratings, and contrast sensitivity significantly predicted MAE duration. This study has, therefore, replicated the trends for group differences in CLCG contrast sensitivity described previously[14] (Michelson contrast thresholds, migraine: 0.3 ± 0.2, control: 0.2 ± 0.1; here, migraine 0.4 ±

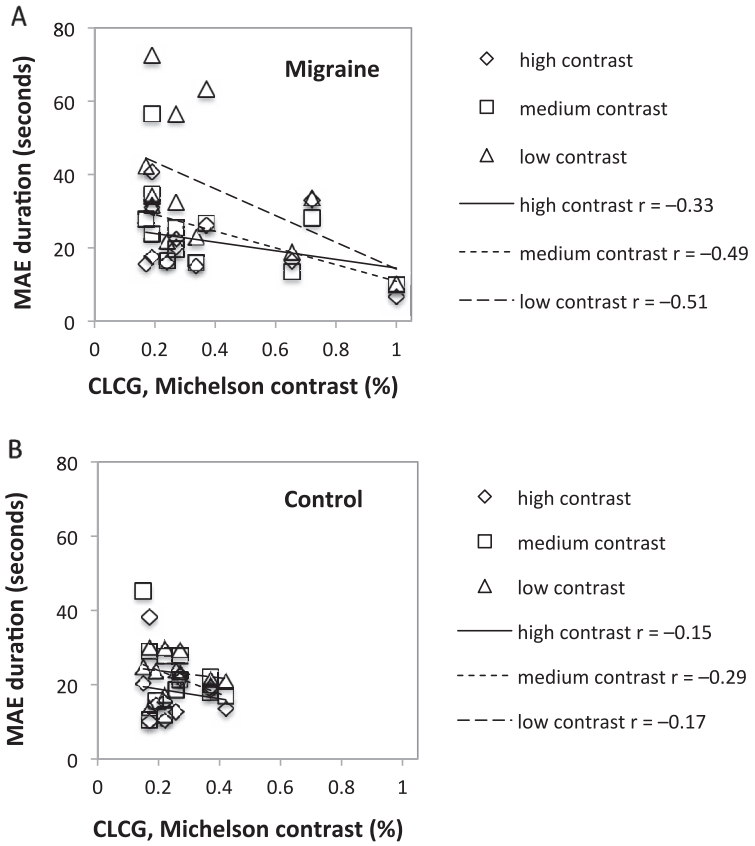

Figure 2. Motion aftereffect duration as a function of contrast sensitivity, as measured by the CLCG, for the migraine (**A**) and control (**B**) groups and for high, medium, and low contrast test displays. CLCG contrast sensitivity ranges from 0.14% to 1% (Michelson contrast). Pearson's correlation coefficients (*r*) are included together with regression lines for each condition.

0.3, control 0.3 ± 0.1). As regards the MAE data, Shepherd[13] used the same adaptation and test display contrast conditions (random dot adapting and test displays, Michelson contrast 30%) and reported comparable results for the group differences presented here: longer MAEs in migraine versus control groups. Furthermore, the trend for impaired contrast sensitivity to be associated with poorer performance on relative motion, motion detection, and motion discrimination tasks[14] also is consistent with the data reported here whereby poorer contrast sensitivity, likely arising from processing in early visual pathways (see prior study[34]), is associated with an impoverished/shorter perception of motion in the duration of the MAE.

The current finding of, on average, prolonged MAEs for low compared to high contrast test displays (Fig. 1) is in line with those of Keck et al.[26] As mentioned in the Introduction, adaptation to motion biases the distribution of activity in direction-selective cells throughout the visual pathways from the retina to cortex, but certainly involving the cortex. As soon as the adapting motion stops, however, the adapted cells start to recover and the length of that recovery, together with any residual response to the test patterns, determines the duration of the MAE. Since the direction-selective cortical cells also are responsive to contrast, the adapted cells would have a larger residual response to the high contrast test patterns than the low, resulting in shorter MAEs for the high contrast test patterns.

Impaired contrast sensitivity results in very low contrasts, which may be discernible to others, appearing uniform and, therefore, undetected. This describes the trend for higher CLCG contrast sensitivity thresholds in migraine. The same logic applied to higher contrasts would mean that higher contrast displays appear to have a lower contrast to the migraine than to the control participants. The result should be a longer MAE in the migraine group, which was found across all three contrast test displays. What also was found here, however, was shorter (not longer) MAEs associated with poor contrast sensitivity in the migraine group, although the association, while sizeable, was not statistically significant. It could be speculated that the medium contrast (Michelson contrast = 30%), chosen to be at or above the contrast level where neuronal response to contrast saturates in the early visual pathways,[35] might not have been sufficiently high to leave the adaptation phase unaffected by impaired contrast sensitivity in migraine. If the adaptation display contrast was perceived as lower in some migraine participants, that is, in those with poor contrast sensitivity, the direction-selective cells would have been less strongly suppressed during the adaptation process. This would result in a slight advantage during the recovery process and result in shorter MAEs in migraine participants with poor contrast sensitivity. Future research might usefully include a range of higher adaptation contrasts.

It can be concluded that contrast sensitivity is relevant to the perception of the MAE, as it predicted MAE duration. The current results suggest an anomaly in early motion processing pathways in migraine that is linked with those pathways underlying contrast sensitivity. It provides further evidence for differences in visual processing that begin early, potentially starting at the level of the retina, which have

consequences for performance on other tasks that putatively examine cortical processing (see also prior reports[14,34,36]). Thus, differences in precortical and cortical visual pathways are implicated in the pathophysiology underlying migraine. An extension of this study that varied adapting contrast, as well as test display contrast, would help to clarify the trends reported here.

Conclusions

This study extends earlier work on motion perception in migraine by assessing one aspect of motion perception, the motion aftereffect, together with an assessment of contrast sensitivity (a person's ability to see faint patterns). This study provides additional evidence that contrast sensitivity is associated with differences in motion processing in migraine.[14] This study replicates earlier reports of enhanced visual aftereffects in migraine, showing that this simple visual test is capable of revealing large group differences, and, thus, may be a useful test to include in clinical trials or to track changes during the migraine cycle. The study also confirms the usefulness of recording additional measures when performing visual tests in migraine, if the aim of the research is to provide evidence for or against models of anomalous visual processing in migraine at particular stages within the visual pathways. Tests of precortical visual processing should be included to preclude the possibility of failing to recognize performance differences for nominally cortical tasks have components attributable to the earlier visual pathways that feed into the cortex.

Acknowledgments

The authors thank Judit Veszeli for collecting some of the data.

Supported by departmental funds (AJS).

Disclosure: **P. Singh**, None; **A.J. Shepherd**, None

References

1. Stovner LJ, Hagen K, Jensen R, et al. The global burden of headache: a documentation of headache prevalence and disability worldwide. *Cephalalgia*. 2007;27:193–210.
2. The Migraine Trust. Available at: http://www.migrainetrust.org. Accessed July 2015.
3. Peatfield RC, Gawal MJ, Rose FC. Asymmetry of the aura and pain in migraine. *J Neurol Neurosurg Psychiatry*. 1981;44:846–848.
4. Rasmussen BK, Olesen J. Migraine with aura and migraine without aura: an epidemiological study. *Cephalalgia*. 1992;12:221–228.
5. Mulleners WM, Aurora SK, Chronicle E, Stewart R, Gopal S, Koehler PJ. Self-reported photophobic symptoms in migraineurs and controls are reliable and predict diagnostic category accurately. *Headache*. 2000;41:31–39.
6. Harle DE, Shepherd AJ, Evans BJW. Visual stimuli are common triggers of migraine and are associated with pattern glare. *Headache*. 2006;46:1431–1440.
7. Shepherd AJ. Models of cortical function in migraine: can psychophysical studies distinguish between them? A review of the evidence for interictal cortical hyper- and hypo-excitability. In: Laura B, ed. *Migraine Disorders Research Trends*. Chapter VI. New York, NY: Nova Science Publishers, Inc.; 2007:145–164.
8. Shepherd AJ. Visual stimuli, light and lighting are common triggers of migraine and headache. *J Light Vis Environ*. 2010;34:40–46.
9. Karanovic O, Thabet M, Wilson HR, Wilkinson F. Detection and discrimination of flicker contrast in migraine. *Cephalalgia*. 2011;31:723–736.
10. Shepherd AJ. Increased visual after-effects following pattern adaptation in migraine: a lack of intracortical excitation? *Brain*. 2001;124:2310–2318.
11. McKendrick AM, Badcock DR. Motion processing deficits in migraine. *Cephalalgia*. 2004;24:363–372.
12. Antal A, Temme J, Nitsche MA, Varga ET, Lang N, Paulus W. Altered motion perception in migraineurs: evidence for interictal cortical hyperexcitability. *Cephalalgia*. 2005;25:788–794.
13. Shepherd AJ. Local and global motion after-effects are both enhanced in migraine, and the underlying mechanisms differ across cortical areas. *Brain*. 2006;129:1833–1843.
14. Shepherd AJ, Beaumont HM, Hine TJ. Motion processing deficits in migraine are related to contrast sensitivity. *Cephalalgia*. 2012;32:554–570.
15. Tibber MS, Kelly MG, Jansari A, Dakin S, Shepherd AJ. An inability to exclude visual noise in migraine. *Invest Ophthalmol Vis Sci*. 2014;55;2539–2546.
16. Verstraten VAJ, Fredericksen RE, van Wezel RJA, Lankheet MJM, van de Grind WA. Recovery from adaptation for dynamic and static motion aftereffects: evidence for two mechanisms. *Vision Res*. 1996;36:421–424.
17. Wade NJ. A selective history of the study of visual motion aftereffects. *Perception*. 1994;23:1111–1134.
18. Hubel DH, Wiesel TN. Receptive fields of single neurones in the cat's striate cortex. *J Physiol (Lond)*. 1959;148:574–591.
19. Hubel DH, Wiesel TN. Receptive fields, binocular interaction and functional architecture in the cat's visual cortex. *J Physiol (Lond)*. 1962;160:106–154.
20. van Wezel RJA, Britten KH. Multiple uses of visual motion. The case for stability in sensory cortex. *Neuroscience*. 2002b;111:739–759.
21. Sutherland S. Figural after-effects and apparent size. *Q J Exp Psychol*. 1961;13:22–228.
22. Mather G, Verstraten F, Anstis SM. *The Motion Aftereffect: A Modern Perspective*. Cambridge, MA: MIT Press; 1998.
23. Barlow HB, Hill RM. Evidence for a physiological explanation for the waterfall phenomenon and figural after-effects. *Nature*. 1963;200:1345–1347.
24. Anstis SM. Motion perception in the frontal plane: sensory aspects. In: Boff KR, Kaufman L, Thomas JP, eds. *Handbook of Perception and Human Performance*. New York: Wiley; 1986:16–21.
25. Nishida S, Ashida H, Sato T. Contrast dependencies of two types of motion aftereffect. *Vision Res*. 1997;37:553–563.
26. Keck MJ, Palella TD, Pantle A. Motion aftereffect as a function of the contrast of sinusoidal gratings. *Vision Res*. 1976;16:187–191.
27. Khalil NM. *Investigations of Visual Function in Migraine Using Visual Evoked Potentials and Visual Psychophysical Tests* [PhD thesis]. London: University of London; 1991.
28. Coleston DM, Chronicle E, Ruddock KH, Kennard C. Precortical dysfunction of spatial and temporal visual processing in migraine. *J Neurol Neurosurg Psychia*. 1994;57;1208–1211.
29. Shepherd AJ. Visual contrast processing in migraine. *Cephalalgia*. 2000;20:865–880.
30. Benedek K, Tajti J, Janaky M, Vecsei L, Benedek G. Spatial contrast sensitivity of migraine patients without aura. *Cephalalgia*. 2002;22:142–145.
31. Headache Classification Subcommittee of the International Headache Society. The international classification of headache disorders: 2nd edition. *Cephalalgia*. 2004;24(suppl 1):24–36.

32. Pelli DG. The Video Toolbox software for visual psychophysics: transforming number into movies. *Spat Vis*. 1994;10:437–442.
33. Delaney HD, Maxwell SE. On using analysis of covariance in repeated measures designs. *Multivar Behav Res*. 1981;16:105–123.
34. Tibber MS, Shepherd AJ. Transient tritanopia in migraine: Evidence for a large-field retinal abnormality in blue-yellow opponent pathways. *Invest Ophthalmol Vis Sci*. 2006;47:5125–5131.
35. Maffei L, Fiorentini A, Bisti S. Neural correlate of perceptual adaptation to gratings. *Science*. 1973;182:1036–1038.
36. Thabet M, Wilkinson F, Wilson HR, Karanovic O. The locus of flicker adaptation in the migraine visual system: A dichoptic study. *Cephalalgia*. 2013;33:5–19.

Investigative Ophthalmology & Visual Science