Available online at www.sciencedirect.com

Vision Research 45 (2005) 2601–2607

Vision Research

www.elsevier.com/locate/visres

Brief communication

Selective attention and cyclopean motion processing

Robert Patterson *, Lisa R. Fournier, Matt Wiediger, Greg Vavrek,
Cheryl Becker-Dippman, Ivan Bickler

Department of Psychology, Washington State University, P.O. Box 644820, Pullman, WA 99164 4820, United States

Received 1 December 2004; received in revised form 9 March 2005

Abstract

The effect of diverted selective attention on the induction of the cyclopean motion aftereffect (aftereffect induced from dynamic disparity information) was investigated. The luminance motion aftereffect was examined for comparison. During diverted-attention trials, observers ignored background adapting motion and performed a low-load or high-load rapid serial visual presentation (RSVP) task presented in the center of the motion display. Baseline motion aftereffects were obtained with no diverted attention. The results showed that the cyclopean motion aftereffect, similar to the luminance motion aftereffect, declined only modestly under diverted-attention conditions. Selective attention appears to play a modest role in the visual processing of cyclopean motion.

Keywords: Cyclopean motion; Stereomotion; Motion aftereffect; Selective attention

1. Introduction

Cyclopean motion refers to the spatiotemporal displacement of binocular disparity, or stereoscopic depth, information (Cavanagh & Mather, 1989; Patterson, 1999). Cyclopean motion is an interesting topic to study because the motion information is processed by disparity-activated mechanisms located at binocular-integration levels of the visual system. Cyclopean motion represents one binocular cue that is used by the visual system to detect the trajectory of objects moving in three dimensions (Regan, 1993).

Some properties of the mechanisms that process cyclopean motion are known. Cyclopean motion is processed by mechanisms that are directionally-tuned (Patterson & Becker, 1996; Phinney, Bowd, & Patterson, 1997) and disparity-tuned (Patterson, Bowd, Phinney, Fox, & Lehmkuhle, 1996). Moreover, cyclopean motion is processed by mechanisms that are tuned to the spatial frequency (Shorter, Bowd, Donnelly, & Patterson, 1999) and temporal frequency of disparity modulation (Shorter & Patterson, 2001), and that compute a form of motion energy applied to the disparity domain (Ito, 1999; Smith & Scott-Samuel, 1998).

One issue currently in dispute is whether selective attention plays a unique role in the visual processing of cyclopean motion. Over the years, a number of authors (e.g., Anstis, 1980; Cavanagh & Mather, 1989; Lu & Sperling, 1995, 2001; Nishida & Ashida, 2000) have suggested that cyclopean motion processing is linked to the operation of selective attention. For example, Lu and Sperling (1995, 2001) have suggested a three-process model to explain human motion perception. In their model, first-order processing involves computing the motion of luminance-defined stimuli, while second-order processing entails computing the motion of texture-defined or contrast-defined stimuli. Third-order processing involves computing the motion of stimuli defined by regions of high perceptual salience, such as cyclopean stimuli.

---

* Corresponding author.
E-mail address: rpatter@mail.wsu.edu (R. Patterson).

0042-6989/$ - see front matter © 2005 Elsevier Ltd. All rights reserved.
doi:10.1016/j.visres.2005.03.003

Presumably moving cyclopean stimuli are processed by a third-order motion system whose input is spatio-temporal variation in feature salience (i.e., feature registered as figure versus ground). Selective attention serves to amplify feature salience, to the degree that it can determine the direction of motion, or even the existence of motion, under certain conditions. Selective attention plays a critical role in the third-order motion system by controlling the strength of input to the system, a kind of attentional gain. According to Lu and Sperling, selective attention plays little role in first-order or second-order motion processing.

In the present study, we investigated the importance of selective attention in cyclopean motion processing. To do so, we examined the effect of attentional modulation on the cyclopean motion aftereffect. For comparison, we also examined the role of attentional modulation on the luminance motion aftereffect. We studied the cyclopean and luminance motion aftereffects within a well-known paradigm (e.g., Chaudhuri, 1990; Rees, Frith, & Lavie, 1997). We had observers perform a low or high attentional-load rapid serial visual presentation (RSVP) task, involving linguistic judgments of single words, while ignoring the presence of adapting cyclopean or luminance motion, and determined whether the cyclopean or luminance motion aftereffect was still experienced. Because Lu and Sperling (1995, 2001) assume that cyclopean motion is processed exclusively by the third-order motion system (and luminance motion would be processed predominately by their first-order motion system), their model would predict that diverted attention would exert a large affect on the cyclopean motion aftereffect and a much smaller effect on the luminance motion aftereffect.

The present study was similar to an investigation by Rose, Bradshaw, and Hibbard (2003), which examined the effect of manipulating attentional load on the stereoscopic depth and motion aftereffect. These authors used moving stereoscopic squares as adapting stimuli, which were created from a random-dot stereogram display. They found that diverting attention away from the adapting stimuli decreased the ensuing depth and motion aftereffect. In contrast to the present study, the Rose et al. investigation did not include a comparison involving the luminance motion aftereffect, and their adapting motion was not cyclopean (i.e., it contained monocular cues).

2. Methods

2.1. Observers

Five individuals served as observers. All observers possessed normal or corrected-to-normal acuity in each eye (tested with Orthorater, Bauch & Lomb) and normal stereopsis (tested with a dynamic random-dot stereogram). All observers were naive as to the hypotheses under test.

2.2. Stimuli

The adapting stimulus was a cyclopean or luminance vertical square-wave grating of spatial frequency 0.5 cyc/deg which moved rightward at a speed of 4°/s (temporal frequency was 2 Hz). The test stimulus was a stationary grating of the same type, orientation, and spatial frequency as the adapting grating. At the beginning of adaptation, the starting phase of the grating was random. During adaptation, bars of the grating went off the right side of the display while other bars appeared on the left side so that continuous motion was generated.

The cyclopean grating was composed of random-dot textured bars that appeared to protrude in depth with a disparity of 11.4′, crossed from the display screen, alternating with bars that appeared in the plane of the display screen with zero disparity (average disparity of the grating was 5.7′). The luminance grating was composed of solid black bars alternating with bars whose regions were filled with red-pixel noise; the luminance grating was defined by differences in luminance, texture, and color, all of which were presented at a disparity value of zero.[1]

In the middle of the motion display, single words were shown within a small blank rectangle (dimensions were 1.52° wide by 0.76° height) that separated them from the stereogram display (the words filled in the area of the rectangle). The rectangle containing the words was positioned in the same depth plane as the closest cyclopean bars during the cyclopean trials and in the plane of the display during the luminance trials. The words appearing within the rectangle and the dots of the stereogram display were always in sharp focus, the former of which provided a fixation stimulus upon which the observers were instructed to fixate.

The word list was composed of 1145 unique words. The word list consisted of one-syllable and two-syllable five-letter words, presented in lower-case or upper-case font. The words (taken from the Coltheart database; Coltheart, 1981) were matched for frequency of occurrence in the English language, and the word lists were similar to those used by Rees et al. (1997).

---

[1] Although the luminance grating was composed of black and red bars defined by differences in luminance, texture, and color, and therefore could be considered a composite of first-, second-, and third-order motion stimuli (Lu & Sperling, 1995, 2001), we assumed that the duration of the motion aftereffect induced by this stimulus would be determined by the component that would generate the longest aftereffect, namely the luminance component. We therefore refer to motion aftereffects induced by our stimulus as luminance motion aftereffects.

2.3. Apparatus

The cyclopean grating was created with a dynamic random-dot stereogram generation system (Shetty, Brodersen, & Fox, 1979). The display device was a 19-in. Barco Chromatics color monitor (refresh rate was 60 Hz; overall display luminance with 50% dot density was 25.2 cd/m^2) upon which matrices of red and green random dots were displayed (approximately 5000 dots per matrix). At a viewing distance of 150 cm, the display subtended $14.06° \times 10.64°$. Observers wore glasses containing red and green chromatic filters which segregated the information presented to the two eyes. The mean luminance of the red and green half-images through their respective filters was 3–4 cd/m^2.

To display the red and green dot matrices, a stereogram generator (hard-wired device) controlled the red and green guns of the Barco monitor. The stereogram generator produced disparity between the two dot arrays by laterally shifting a subset of dots in one eye's view, while leaving unshifted corresponding dots in the other eye's view. The gap created by the shift was filled with randomly positioned dots of the same density and brightness so that no monocular cues were visible. The observer perceived the shifted subset of dots as a set of bars (grating) appearing in depth in front of the background dots of the stereogram display. All dots of the stereogram were replaced dynamically at a rate of 60 Hz, which allowed the grating to be exposed and moved without monocular cues. The duration of the cyclopean grating was controlled electronically in integer-multiples of the frame duration of the display (16.7 ms).

Hidden from the observer, signals from a black and white video camera provided input to the stereogram generator, which determined where disparity was inserted in the stereogram. The camera scanned a black and white square-wave grating moving on a conveyor belt calibrated for speed (accuracy of calibration was checked daily). The stereogram system turned the black and white grating that the camera scanned into a cyclopean grating on the Barco display.

To rule out the presence of monocular cues in the stereogram display, control trials were performed in which observers wore either red or green filters over both eyes and attempted forced-choice direction discrimination of a cyclopean pattern (e.g., grating) that moved either rightward or leftward on each trial, randomly determined. The observers failed to perceive the pattern and direction discrimination was at chance level. The observers also wore red or green filters over both eyes and adapted to a moving cyclopean pattern. The observers never perceived the moving pattern nor experienced an aftereffect. Thus, monocular cues were not present in the stereogram display.

The luminance stimuli were created with the stereogram generation system, which allowed us to present luminance stimuli in the same manner as the cyclopean stimuli. The stereogram generator generated gratings composed of black bars alternating with bars containing dynamic red-pixel noise on the Barco display. Luminance of the red areas was 6.5 cd/m^2, and luminance of the black areas was 0.04 cd/m^2.

A computer display, upon which the words in the RSVP tasks were presented, was optically combined with the view of the Barco display via a beamsplitter such that the words appeared within the blank rectangle in the middle of the motion display.

2.4. Procedure

This study involved a 3×2 within-subjects factorial design. Three levels of attentional load (no load, low load, and high load) were crossed with two levels of motion type (cyclopean, luminance) to create six experimental conditions.

To begin each trial, the observer made a button press that initiated the presentation of the moving cyclopean or luminance adapting grating as well as the sequence of words comprising the RSVP task. In both low-load and high-load conditions, words were rapidly presented during adaptation and the observer was instructed to attend to the word task and to ignore the motion. In the low-load condition, the observer attempted to discriminate upper-case words (targets) from lower case words; in the high-load condition, the observer attempted to discriminate two-syllable words (targets) from one-syllable words. When targets were detected, the observer pressed a key on a keypad within a one-second interval (key presses with latencies longer than one second were scored as errors). The probability that a given word was a target was 0.25. In the no-load condition, a series of five lower- or upper-case 'X's were presented during adaptation, and the observer was instructed to ignore the letters and to attend to the motion (but still fixate the letters). The duration of each word was 750 ms with an ISI of 250 ms (words were presented at a rate of one per second). Following adaptation, the observer viewed a stationary test grating, noted his or her motion aftereffect, and pressed a button on a keyboard to signal the termination of the aftereffect. During the test phase, words were not shown in the rectangle.

To compare the effects of attentional load on the duration of the cyclopean and luminance motion aftereffects, baseline durations under the no-load conditions needed to be similar. However, for a given duration of adaptation, the cyclopean motion aftereffect is known to be shorter than the luminance motion aftereffect (Bowd, Rose, Phinney, & Patterson, 1996; Patterson et al., 1994). Therefore it was necessary for our observers to adapt proportionately longer to cyclopean motion than to luminance motion so that baseline aftereffects of similar duration would be elicited before the attentional-load manipulation was introduced.[2] As indicated by Bowd et al. (1996), an adaptation duration of 192 s for cyclopean motion and 64 s for luminance motion should produce robust aftereffects of nearly equivalent duration. Accordingly, our observers adapted to 192 s of cyclopean motion, or to 64 s of luminance motion, on each trial. In doing so, we assumed that a consistent amount of attentional resource was continuously engaged by the RSVP task during the 192-second adaptation trials as was engaged during the 64-second adaptation trials, an assumption borne out by the equivalence of the accuracy scores for the cyclopean and luminance trials (see Section 3).

Each observer participated in eight sessions. During each session, one motion-aftereffect trial was collected under each of the six conditions. The order of conditions was pseudo-randomly determined for each observer. Thus, a total of eight aftereffect durations were collected under each condition by each observer. Proportion accuracy was obtained for the low-load and high-load RSVP tasks performed in the presence of cyclopean or luminance motion. For trials involving cyclopean motion, there were 48 targets presented out of a total of 192 words on a given trial; median word repetition for the eight sessions was 2.0. For trials involving luminance motion, there were 16 targets presented out of a total of 64 words on a given trial; median word repetition for the eight sessions was 1.0.

3. Results

3.1. Motion aftereffect

Fig. 1 shows aftereffect duration for the cyclopean and luminance motion aftereffects obtained under the no-load, low-load, and high-load conditions. Panel A depicts the averages of our five observers, and Panels B–F show our observers individually. Panel A shows that, on average, attentional load had a modest effect on the two types of motion aftereffect, with aftereffects obtained under the high-load condition being about two-thirds to three-quarters the size of aftereffects obtained under the no-load (baseline) condition. Panels B–F reveal that there were large individual differences among our observers. For three observers, diverted attention had a slightly greater effect on the cyclopean aftereffect than on the luminance aftereffect, but one observer showed an opposite trend and another observer showed no clear trend.

The MAE data shown in Fig. 1A were analyzed by an analysis of variance (ANOVA) for within subject designs, which revealed that attentional load significantly affected aftereffect duration, $F(2, 8) = 7.1$, $p < 0.02$. Tukey's HSD test showed that aftereffect duration in the high-load condition was significantly less than aftereffect durations in the no-load and low-load conditions ($p < 0.05$). The ANOVA also showed that aftereffect duration did not significantly differ between the two types of motion, $F(1, 4) = 0.002$, $p > 0.05$, nor was there a significant interaction between motion type and attentional load, $F(2, 8) = 1.9$, $p > 0.05$.

3.2. RSVP tasks

The proportion of correct responses on the two RSVP tasks, averaged across observers, is shown in Table 1. Table 1 reveals that accuracy for the high-load task was consistently lower by about 0.12 relative to the low-load task.

These data were analyzed by an ANOVA for within-subjects designs. This analysis revealed that attentional load significantly affected accuracy, $F(1, 4) = 29.6$, $p < 0.01$, but that motion type did not, $F(1, 4) = 0.67$, $p > 0.05$. This analysis also revealed that attentional load and motion type did not significantly interact, $F(1, 4) = 3.33$, $p > 0.05$. The significant effect of attentional load on accuracy provided a validity check on the attentional-load manipulation; observers found the high-load task more demanding than the low-load task as shown by the lower accuracy scores for the former (e.g., Rees et al., 1997).

We also computed *t*-tests to determine whether accuracy under the various conditions was significantly less than perfect performance (i.e., a proportion of 1.0). The analyses showed that accuracy was significantly less than a proportion of 1.0 under all conditions ($p < 0.05$).

4. Discussion

The cyclopean motion aftereffect, similar to the luminance motion aftereffect, declined yet remained robust when selective attention was diverted away from the adapting motion by a challenging RSVP task. The duration of both aftereffects remained at 60% of baseline or longer under diverted-attention conditions. The decline of the luminance aftereffect when a high-load task was performed is consistent with other studies (e.g., Chaudhuri, 1990; Rees et al., 1997; Rezec, Krekelberg, & Dobkins, 2004).

During adaptation, the dynamic noise in our luminance grating may have slightly increased the relative

---

[2] Our cyclopean motion aftereffect depends upon having a dynamic display during the test phase (Nishida & Sato, 1995), and it also requires a cyclopean pattern: Shorter et al. (1999, footnote 3) investigated the cyclopean motion aftereffect with three different test patterns: (1) dynamic background dots and static cyclopean grating (as in present study); (2) dynamic dots only; (3) static background dots and static cyclopean grating. They found that significant cyclopean aftereffects were produced with only the first type of display.

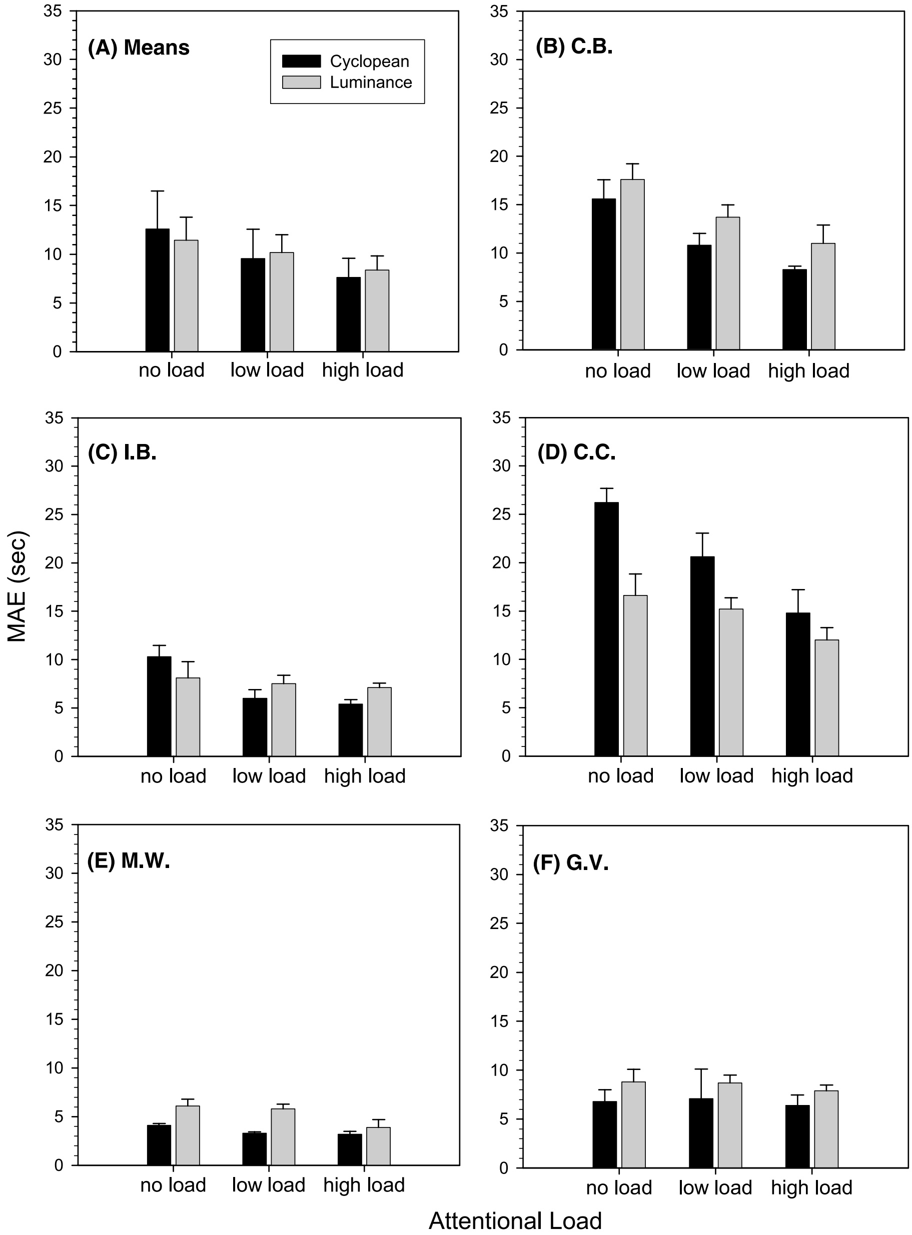

Fig. 1. Motion aftereffect durations for cyclopean and luminance motion under the different attentional-load conditions (no-load, low-load and high-load). Panel A depicts the means of five observers, and Panels B–F show individual observers (for Panels B–F, each bar depicts the mean of eight trials per condition). Error bars show one standard error of the mean.

Table 1
Accuracy scores (proportions) for low-load and high-load tasks performed in the presence of cyclopean or luminance motion

	Attentional load	
	Low load Mean (SE)[a]	High load Mean (SE)[a]
Cyclopean	0.98 (0.003)	0.86 (0.002)
Luminance	0.98 (0.006)	0.87 (0.002)

[a] SE = standard error of the mean.

contribution of a high-level attentional process (Ukkonen & Derrington, 2000), which may have increased the effects of diverted attention on the luminance motion aftereffect. This would slightly diminish the luminance aftereffect, as well as any differences between the cyclopean and luminance aftereffects, found in the present study. Although possible, such an effect of the dynamic noise on the luminance motion aftereffect would not have altered the cyclopean aftereffect, which remained robust under diverted-attention conditions.

The effects of diverted attention are unlikely to be explained via changes in the apparent velocity of the adapting motion. As discussed by Georgaides and Harris (2000), changes in adapting velocity typically affect only the magnitude of the motion aftereffect, while diverted attention affects both magnitude and duration.

We suggest that the cyclopean motion aftereffect is produced by an automatic gain-control process, similar to the luminance motion aftereffect (e.g., van de Grind, van der Smagt, & Verstraten, 2004). We also suggest that the effect of diverted attention is a generic effect on the 'adaptation gain' of a motion system (Rezec et al., 2004); the effects of diverted attention are likely to be similar across the various motion processing streams. Finally, we suggest that cyclopean motion is processed by a second-order motion system, whose front-end filtering involves disparity detection (Cavanagh & Mather, 1989; Patterson, 1999).

The Lu and Sperling model (1995, 2001) (see also Anstis, 1980; Cavanagh & Mather, 1989; Nishida & Ashida, 2000) would predict that diverted attention should exert a large affect on the cyclopean motion aftereffect, one much greater than the luminance motion aftereffect, because cyclopean motion is processed exclusively by a third-order motion system, in which selective attention plays a key role. However, the present results show that diverted attention had only a modest effect on both cyclopean and luminance motion aftereffects. Thus, selective attention does not appear to be uniquely linked to cyclopean motion processing.

More generally, the RSVP linguistic task and the motion displays were shown to depend on a common source of attention because diverting attention to the RSVP task decreased the duration of the motion aftereffect. This shows that attentional resources are not specific to a given type of stimulus, consistent with single-resource models of attention (e.g., Berman & Colby, 2002; Gopher, 1993; Kahneman, 1973; Lavie & Tsal, 1994; Lavie, 1995; Rees et al., 1997, Rees, Frith, & Lavie, 2001).

References

Anstis, S. M. (1980). The perception of apparent movement. *Philosophical Transactions of the Royal Society, London, B, 290*, 153–168.

Berman, R. A., & Colby, C. L. (2002). Auditory and visual attention modulate motion processing in area MT+. *Cognitive Brain Research, 14*, 64–74.

Bowd, C., Rose, D., Phinney, R. E., & Patterson, R. (1996). Enduring stereoscopic motion aftereffects induced by prolonged adaptation. *Vision Research, 36*, 3655–3660.

Cavanagh, P., & Mather, G. (1989). Motion: The long and short of it. *Spatial Vision, 4*, 103–129.

Chaudhuri, A. (1990). Modulation of the motion aftereffect by selective attention. *Nature, 344*, 60–62.

Coltheart, M. (1981). The MRC psycholinguistic database. *Quarterly Journal of Experimental Psychology, 33A*, 497–505.

Georgaides, M. S., & Harris, J. P. (2000). Attentional diversion during adaptation affects the velocity as well as the duration of motion aftereffects. *Proceedings of the Royal Society London B, 267*, 2559–2565.

Gopher, D. (1993). The skill of attentional control: Acquisition and execution of attention strategies. In D. E. Meyer & S. Kornblum (Eds.). *Attention and performance* (Vol. 14, pp. 299–322). Cambridge, MA: MIT Press.

Ito, H. (1999). Two processes in stereoscopic apparent motion. *Vision Research, 39*, 2739–2748.

Kahneman, D. (1973). *Attention and effort*. Englewood Cliffs, NJ: Prentice-Hall.

Lavie, N. (1995). Perceptual load as a necessary condition for selective attention. *Journal of Experimental Psychology: Human Perception and Performance, 21*, 451–468.

Lavie, N., & Tsal, Y. (1994). Perceptual load as a major determinant of the locus of selection in visual attention. *Perception & Psychophysics, 56*, 183–197.

Lu, Z.-L., & Sperling, G. (1995). The functional architecture of human visual motion perception. *Vision Research, 35*, 2697–2722.

Lu, Z.-L., & Sperling, G. (2001). Three-systems theory of human visual motion perception: Review and update. *Journal of the Optical Society of America, A, 18*, 2331–2370.

Nishida, S., & Ashida, H. (2000). A hierarchical structure of motion system revealed by interocular transfer of flicker motion aftereffects. *Vision Research, 40*, 265–278.

Nishida, S., & Sato, T. (1995). Motion aftereffect with flickering test pattern reveals higher stages of motion processing. *Vision Research, 35*, 477–490.

Patterson, R. (1999). Mini-review: Stereoscopic (cyclopean) motion sensing. *Vision Research, 39*, 3329–3345.

Patterson, R., & Becker, S. (1996). Direction-selective adaptation and simultaneous contrast induced by stereoscopic (cyclopean) motion. *Vision Research, 36*, 1773–1781.

Patterson, R., Bowd, C., Phinney, R., Fox, R., & Lehmkuhle, S. W. (1996). Disparity tuning of the stereoscopic (cyclopean) motion aftereffect. *Vision Research, 36*, 975–983.

Patterson, R., Bowd, C., Phinney, R., Pohndorf, R., Barton-Howard, W., & Angilletta, M. (1994). Properties of stereoscopic motion aftereffects. *Vision Research, 34*, 1139–1147.

Phinney, R. E., Bowd, C., & Patterson, R. (1997). Direction-selective coding of stereoscopic (cyclopean) motion. *Vision Research, 37*, 865–869.

Rees, G., Frith, C. D., & Lavie, N. (1997). Modulating irrelevant motion perception by varying attentional load in an unrelated task. *Science, 278*, 1616–1619.

Rees, G., Frith, C. D., & Lavie, N. (2001). Processing of irrelevant visual motion during performance of an auditory attention task. *Neuropsychologia, 39*, 937–949.

Regan, D. M. (1993). Binocular correlates of the direction of motion in depth. *Vision Research, 33*, 2359–2360.

Rezec, A., Krekelberg, B., & Dobkins, K. R. (2004). Attention enhances adaptability: Evidence from motion adaptation experiments. *Vision Research, 44*, 3035–3044.

Rose, D., Bradshaw, M. F., & Hibbard, P. B. (2003). Attention affects the stereoscopic depth aftereffect. *Perception, 32*, 635–640.

Shetty, S. S., Brodersen, A. J., & Fox, R. (1979). System for generating dynamic random-element stereograms. *Behavioral Research Methods and Instrumentation, 11*, 485–490.

Shorter, S., & Patterson, R. (2001). The stereoscopic (cyclopean) motion aftereffect is dependent upon the temporal frequency of adapting motion. *Vision Research, 41*, 1809–1816.

Shorter, S., Bowd, C., Donnelly, M., & Patterson, R. (1999). The stereoscopic (cyclopean) motion aftereffect is selective for spatial frequency and orientation of disparity modulation. *Vision Research, 39*, 3745–3751.

Smith, A. T., & Scott-Samuel, N. E. (1998). Stereoscopic and contrast-defined motion in human vision. *Proceedings of the Royal Society of London, B, 265*, 1573–1581.

Ukkonen, O. I., & Derrington, A. M. (2000). Motion of contrast-modulated gratings is analyzed by different mechanisms at low and at high contrasts. *Vision Research, 40*, 3359–3371.

van de Grind, W. A., van der Smagt & Verstraten, F. A. J. (2004). Storage for free: A surprising property of a simple gain-control model of motion aftereffects. *Vision Research, 44*, 2269–2284.