Vision Research 161 (2019) 43–51

Contents lists available at ScienceDirect

Vision Research

journal homepage: www.elsevier.com/locate/visres

The impact of retinal motion on stereoacuity for physical targets

Matthew D. Cutone[a,*], Robert S. Allison[b], Laurie M. Wilcox[a]

[a] Department of Psychology, York University, Toronto, Canada
[b] Department of Electrical Engineering and Computer Science, York University, Toronto, Canada

ARTICLE INFO

Keywords:
Stereoacuity
Retinal motion
Physical stimuli
Depth discrimination

ABSTRACT

In a series of studies using physical targets, we examined the effect of lateral retinal motion on stereoscopic depth discrimination thresholds. We briefly presented thin vertical lines, along with a fixation marker, at speeds ranging from 0 to 16 deg·s^{-1}. Previous investigations of the effect of retinal motion on stereoacuity consistently show that there is little impact of retinal motion up to 2 deg·s^{-1}, however, thresholds appear to rise steeply at higher velocities (greater than 3 deg·s^{-1}). These prior experiments used computerized displays to generate their stimuli. In contrast, with our physical targets we find that stereoacuity is stable up to 16 deg·s^{-1}, even in the presence of appreciable smearing due to visual persistence. We show that this discrepancy cannot be explained by differences in viewing time, prevalence of motion smear or by high frequency flicker due to display updates. We conclude that under natural viewing conditions observers are able to make depth discrimination judgements using binocular disparity signals that are rapidly acquired at stimulus onset.

1. Introduction

Movement of our head, eyes and objects in the world means that images are often moving across our retinas. The response characteristics of the visual pathway to light leads to perceived smear when luminous stimuli slide across a stationary retina and the extent of the smear increases with increasing retinal stimulus velocity (Burr, 1980). It has been demonstrated that motion smear effectively attenuates energy at high spatial frequencies along the direction of stimulus motion (Morgan and Benton, 1989), reducing its contrast and visibility. Further, while the full extent of this blur is not normally appreciated by observers, it can substantially impact task performance (Bex, Edgar, & Smith, 1995; Burr & Morgan, 1997). In addition to the loss of energy at high spatial frequencies, stimulus motion shifts contrast energy to lower spatial frequencies (Burr & Ross, 1982) causing the visual system to rely on fast, yet low-pass, mechanisms with poorer resolution (Anderson & Burr, 1985; Burr, 1980; for review see Burr & Ross, 1982). Given the impact of motion on our ability to resolve visual stimuli one might expect that so-called hyperacuity performance for tasks such as Vernier and stereoscopic acuity (Westheimer & McKee, 1977, 1978) would be negatively impacted by image motion. Since stereopsis requires precise simultaneous registration of spatial information in *both* eyes, stereoacuity should be particularly susceptible. Westheimer and McKee (1978) compared the resilience of stereoacuity to retinal motion with that of Vernier acuity. They used similar broadband line stimuli, and the same range of target speeds (0 to 2.5 deg·s^{-1}). Observers were asked to fixate a point during the brief stimulus presentation (190 ms) to avoid tracking eye movements. They found that, like Vernier acuity, stereoscopic thresholds were constant over a range of lateral motion speeds of 0 to 2.5 deg·s^{-1}. The line targets used by Westheimer and McKee (1975; 1978) contained a broad range of spatial frequencies, and when set in motion the resultant motion blur would reduce the energy at high spatial frequencies, but lower frequencies would still be available to support disparity processing. Morgan and Castet (1995) later evaluated the spatial-temporal response properties of the neural mechanisms underlying binocular disparity processing. In this study they used spatially narrow band sine wave patterns (presented at a range of velocities and frequencies). Morgan and Castet (1995) reported that, under these conditions, depth discrimination thresholds for moving targets were like those obtained for static targets, but only if the temporal frequency was less than 30 Hz. They concluded that the combined impact of the spatial and temporal attributes was consistent with the phase-based model of disparity processing proposed by DeAngelis, Ohzawa, and Freeman (1991), provided the model units were selective for both spatial and temporal phase. In a more recent study, Ramamurthy, Bedell, and Patel (2005) assessed stereoacuity for broadband targets like those employed by Westheimer and McKee (1977), with retinal motion up to 12 deg·s^{-1}. While their results replicated those of Westheimer and McKee (1978) at low velocities, beyond 3 deg·s^{-1} thresholds rose steeply and monotonically. They attributed threshold elevation to the increase in retinal blur which biased disparity processing to coarse scale disparity-tuned channels (as concluded by Chung, Levi, and Bedell (1996) for Vernier acuity), after discounting the effects of detectability, eccentricity and exposure duration. However, it is not clear how to reconcile these data with those reported by Morgan and

---

[*] Corresponding author.
E-mail addresses: cutonem@yorku.ca (M.D. Cutone), allison@eecs.yorku.ca (R.S. Allison), lwilcox@yorku.ca (L.M. Wilcox).

https://doi.org/10.1016/j.visres.2019.06.003
Received 28 September 2018; Received in revised form 4 June 2019; Accepted 5 June 2019

Table 1
Target properties of vertical line stimuli used to assess stereoacuity thresholds for Westheimer and McKee (1978), Experiment 1 from Ramamurthy et al. (2005), and Experiment 1 from the current study.

	Lateral Velocities (deg·s^{-1})	Target Luminance (cd·m^{-2})	Exposure Duration (ms)	Viewing Distance (m)	Line Width at Viewing Distance (arc minutes)
Westheimer and McKee (1978)	0–2.5	63.66	190	2.5	1
Ramamurthy et al. (2005)	0–12	30	200	3.95	0.2
Experiment 1	0–16	4.2	120	0.5	3

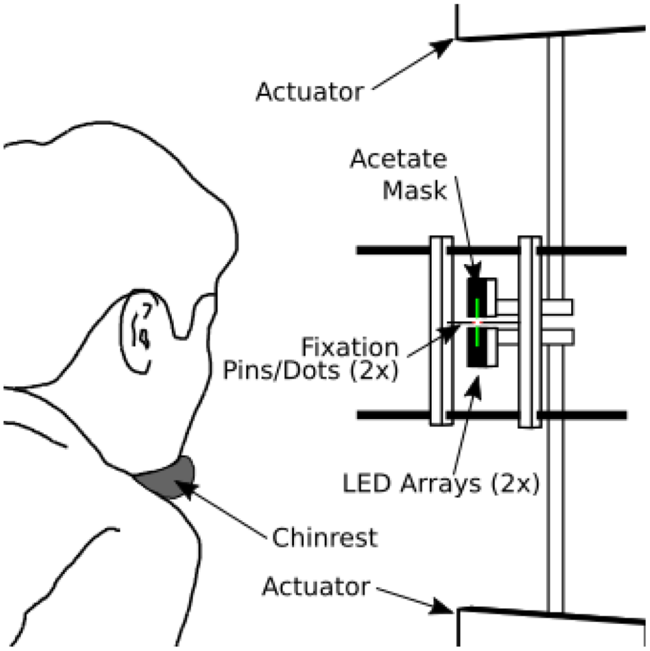


Fig. 1. A simplified schematic of the apparatus (not-to-scale) showing the configuration of key components. Only the luminous green target lines and red fixation dots were visible to the observer during experimental trials.

Castet (1995) whose 30 Hz temporal frequency cutoff corresponded to a velocity of 640 deg·s^{-1} (for a 0.04 cpd grating). There are several differences between these experiments which make it difficult to compare their results (see Table 1), primary among these are the nature of the stimulus used (broad vs. narrow bandwidth), viewing time (restricted vs. unlimited) and the potential for eye movements (Morgan and Castet did not control fixation). It seems clear however that stereoacuity for moving targets depends on a wide range of variables and while there is consensus that retinal motion does not affect stereoacuity at velocities up to approximately 2.5 deg·s^{-1}, the impact of higher velocity motion remains in question.

These earlier experiments used monitors to present moving stereoscopic targets, which contain artifacts not present in real, continuously illuminated, targets. However, distortions in perceived depth can arise due to the display protocol used (Hoffman, Girshick, Akeley, & Banks, 2008) and the presence of inter-ocular delays (Burr & Ross, 1979; Lee, 1970) inherent to the operation of most stereoscopic displays. That is, to create the appearance of a target moving on a display, the image is redrawn repeatedly at multiple discrete locations. In the case of CRT displays, each phosphor scan is followed by a brief interval (this cycle of display and refresh is termed the refresh rate). Thus, the images presented in this manner are stroboscopic. Furthermore, portions of the image are drawn at separate times since the electron beam cannot be at multiple locations at once. Humans rarely encounter objects illuminated in such a fashion in the natural world. Whether flicker is perceived in such displays depends on whether the refresh rate exceeds the temporal integration and Nyquist frequency limits of the visual system (Burr, Ross, & Morrone, 1986; Watson & Ahumada, 1985; Watson, 2013). However, even when smooth motion is perceived during stroboscopic presentation, minute interocular delays of disparate images can produce temporal disparities that may distort perceived depth (Burr & Ross, 1979; Morgan, 1979).

Here we revisit the impact of lateral motion on stereoacuity, using moving physical stimuli that, while producing similar binocular images and motion to those used in previous experiments, (Ramamurthy et al., 2005; Westheimer & McKee, 1978) are free of potential spatio-temporal artefacts introduced by electronic displays. In addition, the use of physical targets avoids the impact of cue conflict between depth from disparity, and other depth cues such as size, parallax, and vergence/accommodation. As Buckley and Frisby (1993) showed, there are substantial differences between performance on depth estimation tasks between computerized stereograms and physical versions, even when the real-world stimuli are carefully controlled to eliminate 2D depth information. Similarly, McKee and Taylor (2010) reported that while observers' depth discrimination performance is precise for physical line targets, when these stimuli are simulated on a mirror stereoscope, thresholds generally increased, indeed some observers could no longer perform the discrimination task.

2. General methods

2.1. Stimuli and apparatus

Stereoscopic depth discrimination thresholds were measured in a manner analogous to that used by Westheimer and McKee (1978) and Ramamurthy et al. (2005) using two dichoptic vertical luminous lines. However, instead of using a computerized graphics display, stimuli were presented using a purpose-built apparatus that allows automated presentation of physical stimuli in a controlled environment (Fig. 1).

The apparatus consists of two sets of computer-controlled motion stages within a light-tight enclosure. Observers viewed the stimuli through an aperture at one end of the enclosure. Each of the two physical line stimuli consisted of a slit that was back illuminated and mounted on a movable rod. The back light consisted of a 2D array of yellow-green (λ_{peak} = 565 nm) light emitting diodes encased in a light diffusing translucent resin (LiteOn Inc. LTL-2885G). A vertical slit mask was applied to the face of the array producing a 30 by 3 arcmin line when viewed at 50 cm. The rods holding the line stimuli were positioned using two-dimensional motorized actuators, one mounted below the stimulus on the optical bench (below) and the other directly above it on the ceiling of the apparatus frame. Each actuator had a positional repeatability of ± 0.025 mm and the specified positional error (0.04%) was negligible given the travel of the stimuli was no more than a few centimeters. The actuators were driven using stepper motors controlled by a Galil DMC-4050 motion controller. The stimulus placement was verified by examining the output of high-resolution optical encoders attached to the driveshaft of each stepper motor. Stimuli were presented in darkness to hide all staging equipment.

Target lines were presented about a fixation marker located 50 cm from the participant's cyclopean eye. This marker was composed of two fiber optic wires which terminated on the end of metal pins and were positioned in the gap between the lines, facing the observer and gave the appearance of small red dots when illuminated. Their horizontal angular separation was 30 arc minutes. The actuators controlled the lateral and in-depth position and motion of the targets relative to the fixation stimulus. In all experiments, the lines were configured so that one was positioned above and one below fixation, with a vertical end-to-end separation of 25 arc minutes. The two lines were aligned laterally and moved in unison. The horizontal velocity of the lines ranged from 0 to 16 deg·s^{-1}; the range of motion was centered about the fixation points and the initial direction of motion for each trial was randomized to prevent anticipatory eye movements. The lines could be offset in depth relative to the fixation target to introduce binocular disparity.

The exposure duration was fixed at 120 ms unless otherwise specified, an interval too brief to initiate pursuit eye movements (Westheimer, 1954). The target lines were illuminated via digital output from the motion controller at the point the controller registers the target velocity has been achieved, following a brief acceleration interval which served to dampen jerk and minimize potential artifacts caused by vibration. After the exposure interval elapsed, the lines were switched off and repositioned for the next trial. Target and fixation brightness were adjusted prior to testing to a level that did not produce perceptible afterimages after 190 ms exposure, to avoid potential effects of negative afterimages on observers' depth judgements (Lugtigheid, Wilcox, Allison, & Howard, 2013; Shortess & Krauskopf, 1961). The luminance of the lines was 4.2 cd·m^{-2}, measured using a photometer (Konica Minolta LS-100) from 50 cm.

3. Experiment 1: stereoacuity for laterally moving physical targets

3.1. Participants

Five people participated in this experiment, ranging in ages 18–30 years. All participants had normal or corrected-to-normal visual acuity, and stereoacuity of at least 40 arc seconds of disparity on the Randot™ Preschool Stereotest. In addition, they all had prior experience as participants in psychophysical studies of stereopsis. In all studies reported here informed consent was gathered from participants prior to participation. Furthermore, all procedures were in accordance with the Code of Ethics of the World Medical Association (Declaration of Helsinki) and were approved by York University's ethics board.

3.2. Procedure

At the start of each trial, participants were instructed to fixate on the illuminated fixation points, and when ready, to initiate stimulus presentation by pressing a button on a game pad. The fixation dots immediately switched off, and the target presentation was initiated. After target exposure, the fixation dots reappeared, and the observer was asked to report whether the top line was 'nearer' or 'farther' to themselves than the bottom reference line. The reference line was always presented at the same distance as the fixation points, and the test line was displaced some distance in depth. A brief tone indicated the start of the next trial. The method of constant stimuli was used to select the depth offset presented on each trial. Target line depths were specified using disparity by accounting for each person's interocular distance as measured using a pupilometer (Shin-Nippon PD-82). The proportion 'nearer' responses were fitted with a psychometric function that has the shape of a cumulative normal function (Wichmann & Hill, 2001) using maximum-likelihood estimation (Knoblauch & Maloney, 2012). Thresholds were computed by taking the difference between the fitted 0.75 and 0.5 points on the curve. Each of the eleven disparities were presented ten times at each speed (0, 2, 4, 8, and 16 deg·s^{-1}) in separate, randomized blocks. The size of the disparity step was determined for each observer in pilot sessions.

3.3. Results and discussion

Fig. 2 shows mean thresholds for the participants as a function of velocity. The data was fitted with a linear mixed-effects model (LMM) using the 'lme4' package (Bates, Machler, Bolker, & Walker, 2015) within the R software environment (R Core Team, 2017), where subject was specified as a non-independent grouping variable. An ANOVA applied to the model shows no significant overall effect of increasing velocity on stereoacuity [$F(4, 16) = 1.1823$, $p = 0.3559$, $\Omega^2 = 0.68$] across the entire range of test velocities. Thus, there is no appreciable increase in thresholds at velocities in the range of 0 to 16 deg·s^{-1}.

It is tempting to conclude that relatively stable thresholds obtained here are solely due to our use of physical targets since our study was designed to closely replicate the test conditions used by both Westheimer and McKee (1978) and Ramamurthy et al. (2005). However, as outlined below, on its own Experiment 1 does not explain why thresholds are so resilient to motion smearing, nor does it rule out the possibility that additional depth cues are available and serve to stabilize thresholds when judging relative depth of our physical targets in motion.

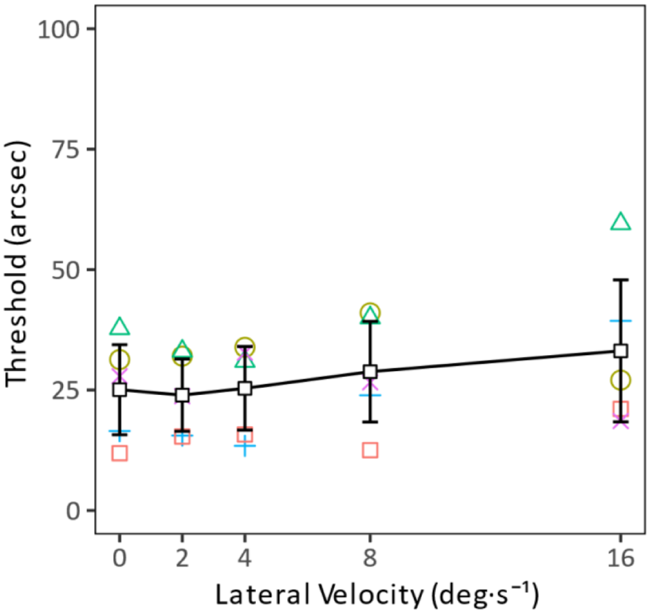


Fig. 2. Averaged participant thresholds ($n = 5$) for each test velocity. Error bars represent the 95% confidence interval for each data point computed using the formula $\boldsymbol{CI} = \bar{\boldsymbol{X}} \pm 1.96 \times \left(\frac{\sigma}{\sqrt{n}}\right)$. Individual observer thresholds for each velocity are represented by coloured glyphs (see Appendix A for psychometric function fits used to compute these thresholds).

4. Experiment 2: contribution of monocular depth cues

In Experiment 1 effort was made to control monocular depth cues to isolate binocular disparity, however, some cues such as motion parallax (the relative speed and positions of the two lines), accommodation and relative size were not controlled for due to the physical constraints of our apparatus. It is possible that the presence of these additional depth cues, which were absent in the virtual targets used by Ramamurthy et al. (2005), contributed to the low thresholds observed in Experiment 1. To evaluate this possibility, we replicated Experiment 1 under monocular viewing. If monocular cues served to reduce thresholds in the preceding experiment, participants should be able to exploit those cues when they are presented in isolation.

4.1. Participants

A total of five people participated in this experiment with ages ranging between 18 and 30. Four of the participants previously participated in Experiment 1. All participants had normal or corrected-to-normal visual acuity and demonstrated the ability to perceive depth through binocular disparity using the Randot™ Stereoacuity Test with a threshold less than 40 arc seconds.

4.2. Procedure

The apparatus and stimuli were identical to that described in Experiment 1, with the modification that participants wore an eye-patch over their non-dominant eye to ensure that only monocular depth cues were available to support the discrimination judgment. The procedure followed that described in General Methods, with the exception that only three lateral velocities were tested (0, 8, and 16 deg·s^{-1}) in separate blocks sequenced randomly. We anticipated that thresholds would be elevated so step sizes were increased accordingly (to 40 arc seconds).

4.3. Results & discussion

It was not possible to fit a reasonable psychometric function to any participant's data; as responses varied considerably all test disparities. This is evident in Fig. 3 which shows the averaged proportion 'nearer' response data as a function of the equivalent disparity of the monocular depth between the bars. Clearly observers could not reliably perform this task using monocular cues alone. Therefore, it is not plausible that the consistently low thresholds in Experiment 1 were due to the presence of reliable monocular depth cues in our physical stimuli.

5. Experiment 3: effect of exposure duration on stereoacuity

Westheimer and McKee (1978) suggested that several discrete samples of the binocular disparity signals are averaged over a presentation interval, making the stereoscopic system resilient to motion blur. However, there is little evidence for this type of sampling mechanism in the existing literature. Furthermore, one would expect elevated thresholds at higher velocities under this hypothesis, as motion blur or streaking results in less precise disparity information if sampling continuously from moving targets. We propose instead that depth is acquired very quickly from the disparity signal at stimulus onset, prior to the image being smeared by motion. This proposal is consistent with reports that the visual system can extract disparity from very briefly presented targets (Caziot, Backus, & Lin, 2017; Caziot, Valsecchi, Gegenfurtner, & Backus, 2015; Dove, 1841; Foley & Tyler, 1976; Kumar & Glaser, 1994; Ogle & Weil, 1958; Uttal, Davis, & Welke, 1994; Valsecchi, Caziot, Backus, & Gegenfurtner, 2013). For instance, Ogle and Weil (1958) found stereoscopic thresholds for lines rose with decreasing exposure duration, but thresholds were relatively stable at durations between 10 and 200 ms. Similarly, Kumar and Glaser (1994) showed that for practiced observers, stereoacuity thresholds varied little with exposure duration between 5 and 100 ms. To confirm that observers could extract depth from binocular disparity very rapidly with our physical line stimuli, we measured stereoacuity for static versions of the stimuli used in Experiment 1, presented at a range of exposure durations. If observers are capable of rapidly processing relative disparity in Experiment 1, thresholds should be comparable to those obtained using static stimuli even at extremely brief exposure durations.

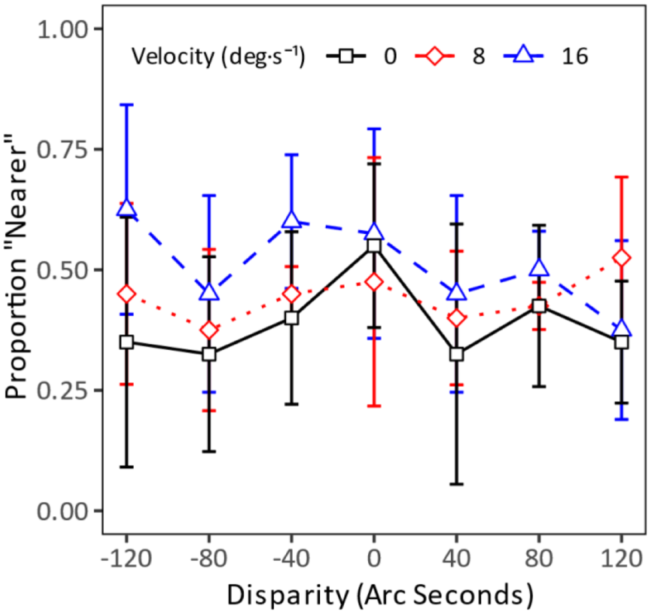


Fig. 3. Averaged proportion 'nearer' responses during monocular viewing for all observers ($n = 5$). Data are plotted as a function of the disparity equivalent to the monocularly presented depth. Error bars represent 95% confidence intervals.

5.1. Participants

The participants were the same individuals tested in Experiment 2.

5.2. Stimulus and procedure

The luminous lines were the same as those used in Experiment 1. However, in this study they remained stationary, and only their exposure duration and relative separation in depth were varied. The use of physical LED stimuli proved advantageous here, as the purpose-built timing circuit permitted μs precision in exposure with negligible persistence when switched off. Luminance was suprathreshold and did not appear to change across exposure durations, though this was not measured directly. Six exposure durations were selected (10, 20, 40, 80, 120, and 190 ms) for this experiment. Each exposure duration was tested in separate, randomized blocks of 10 trials each.

5.3. Results & discussion

Fig. 4 shows a plot of mean thresholds for each exposure duration. A linear mixed-model was fitted to the data and an ANOVA performed on the model revealed an insignificant decrease in stereoscopic depth thresholds with increasing duration [$F(5, 20) = 2.693$, $p = 0.051$, $\Omega^2 = 0.76$]. A pairwise t-test showed a significant difference in thresholds obtained at the shortest and longest durations [$t(4) = 10.89$, $p < 0.01$]. However, the mean of the differences is only ~3.57 arc seconds and there is substantial overlap of confidence intervals. Therefore, subjects performed comparably over this range. Importantly, the results at the shortest durations tested here support our hypothesis that observers can rapidly extract depth from disparity for these stimuli.

6. Experiment 4: subjective measurements of stimulus smear size

We found in Experiment 1 that stereopsis was unaffected by lateral velocities up to 16 deg·s^{-1}. Ramamurthy et al. (2005) attributed the dramatic rise in thresholds in their study to increasing retinal smear at higher velocities. As outlined in the Introduction, smearing is expected to attenuate high spatial frequencies and shift the processing of depth information to less precise, low-frequency visual mechanisms. Although the stimuli configuration and task in Experiment 1 were very similar to those of Ramamurthy et al. (2005), differences in luminance, line thickness, and viewing conditions may have resulted in less motion smear over a larger range of velocities. One might expect thresholds to be relatively stable if smearing is reduced or negligible.

While we do not know how much smear was present in the stimuli used by Ramamurthy et al. (2005), we can evaluate if motion smearing did occur in our stimuli, and if so to what degree. We accomplished this by asking observers to judge the total apparent width of the line targets including any visible smear, following presentation at each test velocity.

6.1. Participants

The five observers who participated in Experiment 2 also participated in this experiment.

6.2. Method and procedure

The line stimuli described in General Methods were used here, but were presented binocularly with zero relative disparity, at a viewing distance of 50 cm. Observers indicated the perceived width of the line in motion using an onscreen ruler displayed on a laptop screen, located on a desk 80 cm to the right of the observer. The ruler consisted of a thin white line on a black background whose length was adjusted using a computer mouse. The observer clicked a button on the mouse to submit a response, which was then converted from length in pixels to degrees of visual arc. Observers indicated

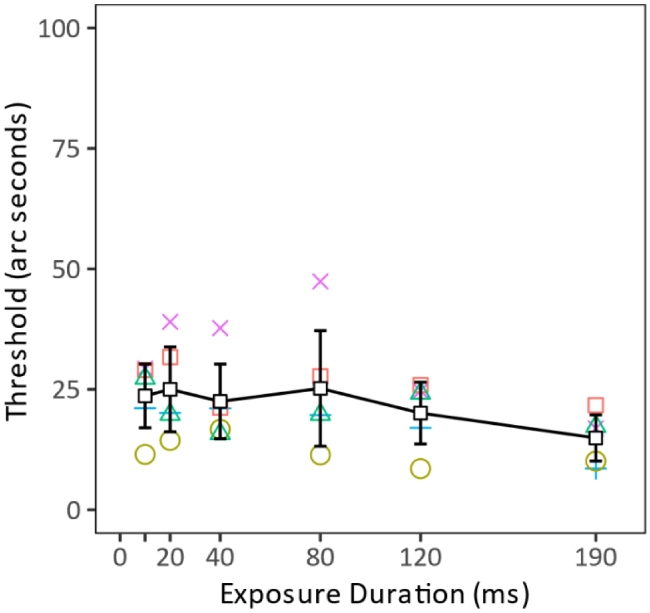


Fig. 4. Mean thresholds for all observers ($n = 5$) at each exposure duration measured in Experiment 3. The open squares are the average thresholds for each exposure duration condition. Error bars represent the 95% confidence interval. The colored glyphs represent an individual observer's fitted threshold (see Appendix A for psychometric function fits).

verbally when to commence the trial. The experimenter then triggered presentation of the moving lines, afterwards observers adjusted the width of the onscreen ruler to match the perceived horizontal width of the moving line stimuli at the end of the motion interval. Five lateral velocities were tested (0, 2, 4, 8, and 16 deg·s^{-1}) in separate blocks in random order consisting of 10 trials each, for a total of 50 trials.

6.3. Results

Fig. 5 displays the averaged smear width in degrees as a function of velocity. A repeated-measures ANOVA applied to the fitted LMM model expresses a significant effect of motion on perceived smear size [$F(4, 16) = 19.263$, $p < 0.001$, $\Omega^2 = 0.84$]. The results indicate that, on average, the width of the perceived smear increases with rising velocity; in agreement with previous research on perceived smear in relation to retinal velocity under fixation (Burr & Morgan, 1997; Burr, 1980; Chen, Bedell, & Öğmen, 1995; Morgan & Benton, 1989). The data shows no significant change in smear extents between 0 and 2 deg·s^{-1} [$t(24) = 0.0467$, $p = 0.963$], however there are significant increase between 0 and 4 deg·s^{-1} [$t(24) = 5.2762$, $p < 0.01$] and beyond. From this we can conclude that observers in Experiment 1 perceived smearing of stimuli at velocities greater than 2 deg·s^{-1}. Thus, the lack of effect of velocity in our study cannot be attributed to an absence of apparent motion smear. The angular extent of the smear agrees with the findings of Chen et al. (1995), who found a vertically arranged file of dots produced perceptible traces with approximately similar horizontal extents at 120 ms exposures. Furthermore, the increase in perceived smear beyond 2 deg·s^{-1} corresponds to the point where Ramamurthy et al. (2005) indicated blur due to visual persistence would have a significant impact on stereoscopic depth thresholds. However, even with the increase in smear, we did not observe a significant rise in thresholds. The question remains why were participants able to acquire and exploit the disparity signal in this study and not in that of Ramamurthy et al. (2005)?

7. Experiment 5: display flicker and stereoacuity

Given the results of Experiments 1–4, it seems that a likely source of the difference between our results and those of Ramamurthy et al. (2005) is the use of physical targets versus stimuli rendered using a stroboscopic display. In this experiment we investigate whether the 240 Hz periodic refresh used by Ramamurthy et al. (2005) could explain the difference between their results and the present study.

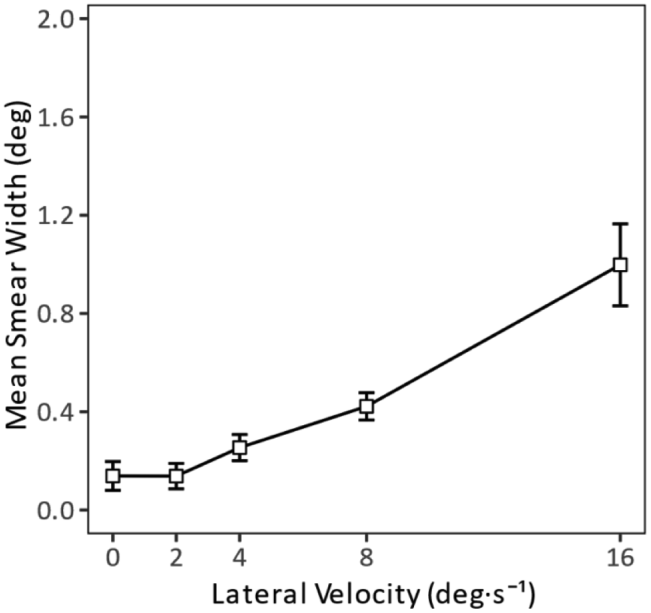


Fig. 5. Mean perceived smear width for all observers ($n = 5$) at each retinal velocity. Error bars represent the 95% confidence intervals. The dashed line indicates the total distance in degrees of arc traversed by the target lines for the given exposure duration.

7.1. Participants

The five observers that participated in Experiment 2 participated in this experiment.

7.2. Apparatus and procedure

This experiment was identical to Experiment 1 but with the addition of a 240 Hz flicker to the line targets. Flicker was accomplished using an astable oscillator integrated circuit connected to a transistor that gated power to the target lines independent of the exposure control circuit. The oscillator produced a 240 Hz square-wave signal with an on-time of approximately 300 µs (duty cycle of 7.2%). When flickered, the perceived luminance of the line targets was reduced relative to the continuously illuminated lines. To compensate, flickering and continuously illuminated lines were perceptually matched prior to the main experiment by three of the observers. To do so, the lower line in the standard configuration was stationary and continuously illuminated, while top line was driven by the oscillator (to introduce flicker). The resistance across the rheostat was adjusted and measured (Fluke 8840A Multimeter) in isolation from the rest of the circuit. In this matching phase observers had unlimited viewing time and indicated verbally when the two lines appeared to have the same luminance. Three observers performed 10 matches each, the average of these settings was used to determine the appropriate resistance to use to set the luminance of the flickering lines in the subsequent discrimination experiment.

Prior to the main experiment, each of the five observers first viewed the flickering and continuously illuminated lines to confirm that they appeared equally bright. Stereoacuity was measured as described in the General Methods section, with the flickering target and reference lines, at five test velocities (0, 2, 4, 8, and 16 deg·s^{-1}) each tested in a separate block in random order. The step sizes for each observer were similar to those used in Experiment 3. For comparison, thresholds were also measured for continuously visible (non-flickering) targets at 0 and 16 deg·s^{-1}.

7.3. Results

Fig. 6 shows the mean stereoacuity ($n = 5$) for flickering and continuous line targets as a function of velocity. The pattern of results is very similar to Experiment 1, where stereoscopic discrimination thresholds seem to be relatively stable over the entire range of velocity conditions. Thresholds for these flickering lines do not differ between control conditions at 0 and 16 deg·s^{-1} indicating no effect of stroboscopic presentation. An ANOVA applied to a fitted LMM on the 240 Hz data does show a significant effect of lateral velocity [$F(4, 16) = 3.289$, $p = 0.0379$, $\Omega = 0.44$]. However, the range of thresholds is comparable to those obtained in Experiment 1, and again we did not observe the sudden rise in thresholds reported by Ramamurthy et al. (2005). Pairwise *t*-tests showed no significant difference between flickering and non-flickering conditions at 0 and 16 deg·s^{-1}. In sum, while there is a slight effect of introducing motion in this study, there is no effect of 240 Hz flicker on stereoacuity when compared to continuously illuminated targets; we conclude that the differences between our results and those of Ramamurthy et al. (2005) cannot be explained by the temporal variation introduced by the refresh rate of the CRT display. These results are consistent with prior studies examining the effect of temporal frequency on stereoacuity thresholds.

8. Discussion

We have shown that, for physical targets, stereoscopic discrimination thresholds remain near the threshold for stationary stimuli (20–30 arcsec) when retinal images move laterally, up to 16 deg·s^{-1}. This was true even though the movement caused significant image smear. Further, thresholds for these stimuli were not substantially affected by introducing a stimulus onset delay, or by adding a 240 Hz flicker. Additional depth cues present in these physical targets cannot account for the resilience to retinal motion; on their own, monocular cues cannot be used to perform the task.

The robustness of stereoacuity shown here was unexpected considering prior evidence that retinal motion degrades Vernier acuity (Chung et al., 1996) and stereoscopic depth thresholds (Ramamurthy et al., 2005) under similar test conditions for broadband line targets. As outlined in the Introduction, Morgan and Castet (1995) have also reported that stereoacuity is unaffected by image motion, as long as the temporal frequency of their narrow band targets was less 30–40 Hz. However, unlike our study they presented their stimuli with prolonged viewing time and unrestricted fixation, which makes it very difficult to directly relate the two studies. In contrast Ramamurthy et al. (2005) reported that thresholds increased rapidly with stimulus speed beyond 3 deg·s^{-1}. Their protocol was similar to that used in the present study and employed by Westheimer and McKee (1977). The results of the present experiments indicate that the stereopsis is much more robust to retinal image motion than suggested by Ramamurthy et al. (2005).

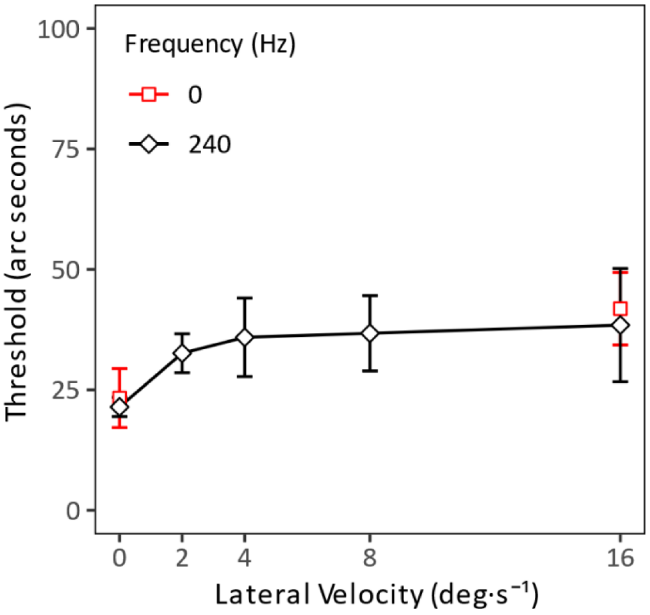


Fig. 6. Averaged thresholds for observers ($n = 5$) viewing flickering (black squares) and continuously illuminated (red triangles) laterally moving stimuli. Error bars represent 95% confidence intervals. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

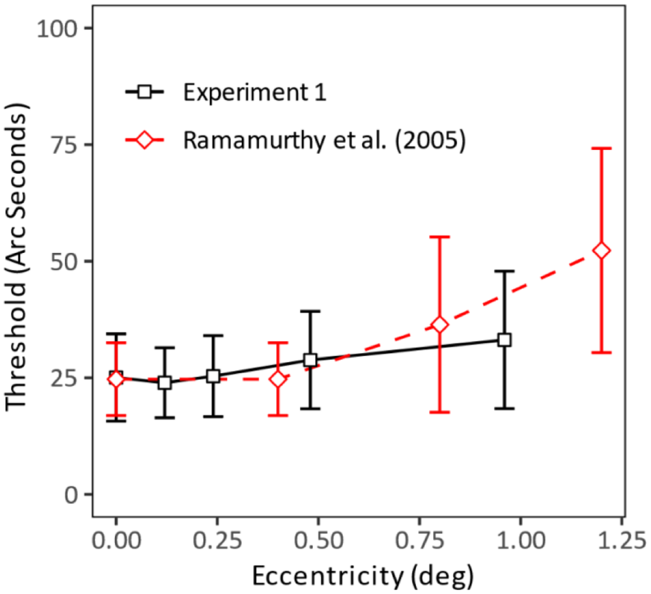


Fig. 7. Superimposition of static onset eccentricity stereoscopic depth thresholds reported by Ramamurthy et al. (2005) in their Experiment 4 (Table 2) and the stereoscopic discrimination thresholds for moving lines from Experiment 1 presented in terms of onset eccentricity. Error bars represent one standard error. Note that exposure durations differed between studies resulting in the lines having different onset eccentricities at similar velocities.

Taken together, our experiments suggest that the stereoscopic system can exploit the transient disparity signal at stimulus onset. This disparity signal can be thought of as a three-dimensional snapshot, which is processed while the physical stimulus moves to another retinal location, making it immune to the disruptive effects of motion blur from retinal and cortical sources. If our proposal is correct then we would expect that acuity would be limited not by velocity, but by other factors known to influence stereoacuity such as contrast, exposure duration, and eccentricity. While our stimuli were always clearly visible, to ensure that they were centered on fixation, the horizontal distance from fixation at onset increased with increasing speed. At our highest velocity (16 deg·s^{-1}), the stimuli became visible at roughly 1 degree of eccentricity. Given that several studies (Blakemore, 1970; Hirsch & Weymouth, 1948; Rawlings & Shipley, 1969; Shipley & Popp, 1972) suggest that stereoscopic depth thresholds increase with eccentricity in the parafovea, under our proposal we might predict an increase in thresholds with stimulus velocity due to the associated increase in onset eccentricity. However, consistent with our results with moving stimuli, Ramamurthy et al. (2005) reported that the eccentricity of static versions of their stimuli had only a minor influence on depth thresholds up to 1.2 degrees. A direct comparison between the results of both studies can be seen in Figs. 7.

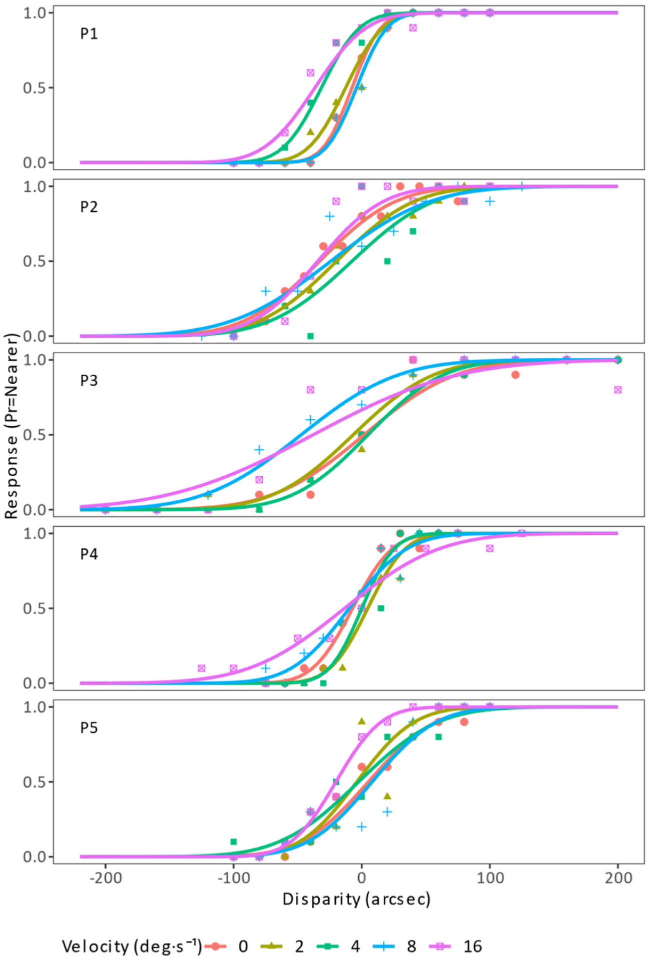
The question remains why stereoacuity for Ramamurthy et al. (2005) two observers increased so markedly as a function of velocity at speeds greater than 3 deg·s^{-1} while our observers consistently maintained thresholds near 25 arcsec. Experiment 5 rules out explanations based on flicker caused by the CRT refresh rate. In addition to the flashed versus continuous nature of the stimulus display there are a number of other differences between the studies. Our study used physical motion of a real object while Ramamurthy et al. used mirrors to move the pair of halfimages in a stereoscope. Differences in the dimensions and luminance between stimuli provides another possible explanation for the discrepancy in results at higher velocities between Ramamurthy et al. (2005) and this study. The physical lines used here were wider (3 arcmin) than those used by Ramamurthy et al. (0.2 arcmin). Thus, the energy in our physical line stimuli is concentrated at lower spatial frequencies than in the narrower line stimuli used by Ramamurthy et al. (2005). Given that high spatial frequencies are attenuated more than low frequencies by motion (Burr & Ross, 1982), our stimuli would be more resilient to the attenuation effects of motion. That is, in Ramamurthy et al.'s case, motion would have a potentially larger impact on stimulus contrast, reducing visibility and therefore increasing thresholds. While this explanation is appealing, Ramamurthy et al.'s stimuli were a factor of 7 brighter than ours (30 cd·m^{-2} versus 4.2 cd·m^{-2}), a difference that should largely offset the difference in spatio-temporal bandwidth between them, resulting in similar energy at frequencies relevant to the discrimination task (see Supplementary Material). This, and the fact that Ramamurthy et al. (2005), show no effect of reducing stimulus contrast (by a factor of 9) on stereoacuity, over this range of velocities, suggests that the relative visibility of the stimuli cannot explain the differences in our patterns of results. It is likely that small methodological differences combine to explain the sensitivity of Ramamurthy et al.'s two observers compared to the relative tolerance to motion that we report.

Our use of physical targets in this experiment was designed to give ecological validity. In the real world we are often called to make rapid judgements of moving objects. Under these conditions relative disparity appears to be extracted and processed without interference by retinal motion, at least up to a velocity of 16 deg·s^{-1} Our results are consistent with long-standing evidence that binocular disparity can support relative depth judgements at very short exposure durations (Dove, 1841; Ogle & Weil, 1958) and suggest that an important consequence of this ability is the provision of depth information for moving objects.

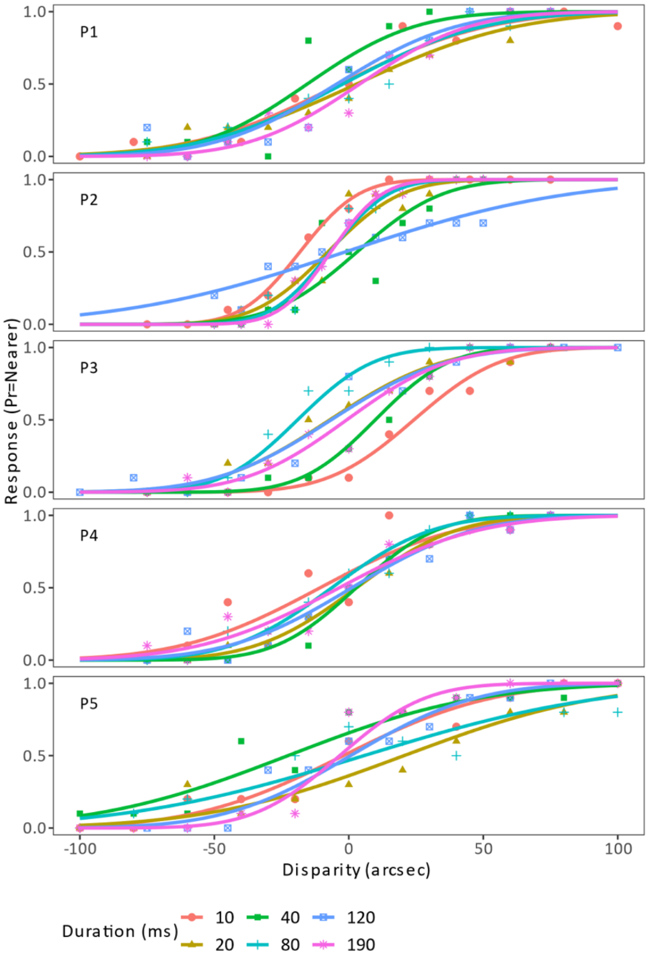
Acknowledgements

The authors would like to thank Jenny Read for helpful comments during the review process. The Natural Sciences and Engineering Research Council of Canada (NSERC) funded this research. The grant numbers are: RGPIN-422631-2012, RGPIN-203634-2012, and RGPIN-06732-2015.

Appendix A



Appendix 1. Raw psychometric function fits for participants (P1-P5) for each velocity in Experiment 1.



Appendix 2. Raw psychometric function fits for participants (P1-5) in Experiment 3 for each exposure duration.

Appendix B. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.visres.2019.06.003.

References

Anderson, S. J., & Burr, D. C. (1985). Spatial and temporal selectivity of the human motion detection system. *Vision Research, 25*, 1147–1154.

Bates, D., Machler, M., Bolker, B., & Walker, S. (2015). Fitting linear mixed-effects models using lme4. *Journal of Statistical Software, 67*, 1–48.

Bex, P. J., Edgar, G. K., & Smith, A. T. (1995). Sharpening of drifting, blurred images. *Vision Research, 35*, 2539–2546.

Blakemore, C. (1970). The range and scope of binocular depth discrimination in man. *The Journal of Physiology, 211*(3), 599.

Buckley, D., & Frisby, J. P. (1993). Interaction of stereo, texture and outline cues in the shape perception of three-dimensional ridges. *Vision Research, 33*, 919–933.

Burr, D. (1980). Motion smear. *Nature, 284*, 164–165.

Burr, D. C., & Morgan, M. J. (1997). Motion deblurring in human vision. *Proceedings of the Royal Society of London. Series B: Biological Sciences, 264*(1380), 431–436.

Burr, D. C., & Ross, J. (1979). How does binocular delay give information about depth? *Vision Research, 19*, 523–532.

Burr, D. C., & Ross, J. (1982). Contrast sensitivity at high velocities. *Vision Research, 22*, 479–484.

Burr, D. C., Ross, J., & Morrone, M. C. (1986). Smooth and sampled motion. *Vision Research, 26*, 643–652.

Caziot, B., Backus, B. T., & Lin, E. (2017). Early dynamics of stereoscopic surface slant perception. *Journal of Vision, 17*(14), 4.

Caziot, B., Valsecchi, M., Gegenfurtner, K. R., & Backus, B. T. (2015). Fast perception of binocular disparity. *Journal of Experimental Psychology: Human Perception and Performance, 41*(4), 909–916.

Chen, S., Bedell, H. E., & Öğmen, H. (1995). A target in real motion appears blurred in the absence of other proximal moving targets. *Vision Research, 35*(16), 2315–2328.

Chung, S. T., Levi, D. M., & Bedell, H. E. (1996). Vernier in motion: What accounts for the threshold elevation? *Vision Research, 36*, 2395–2410.

DeAngelis, G. C., Ohzawa, I., & Freeman, R. D. (1991). *Nature, 352*, 152–159.

Dove, H. W. (1841). Über die Combination der Eindrücke beider Ohren und beider Augen zu einem Eindruck. *Monatsberichte der Berliner preussische Akademie der Wissenschaften, 41*, 251–252.

Foley, J. M., & Tyler, C. W. (1976). Effect of stimulus duration on stereo and vernier displacement thresholds. *Attention, Perception, & Psychophysics, 20*, 125–128.

Hirsch, M. J., & Weymouth, F. W. (1948). Distance discrimination: II. Effect on threshold of lateral separation of the test objects. *Archives of Ophthalmology, 39*(2), 224–231.

Hoffman, D. M., Girshick, A. R., Akeley, K., & Banks, M. S. (2008). Vergence–Accommodation conflicts hinder visual performance and cause visual fatigue. *Journal of Vision, 8* 33 33.

Knoblauch, K., & Maloney, L. T. (2012). *Modeling psychophysical data in R.* New York: Springer.

Kumar, T., & Glaser, D. A. (1994). Some temporal aspects of stereoacuity. *Vision Research, 34*(7), 913–925.

Lee, D. N. (1970). Spatio-temporal integration in binocular-kinetic space perception. *Vision Research, 10*, 65–78.

Lugtigheid, A. J., Wilcox, L. M., Allison, R. S., & Howard, I. P. (2013). Vergence eye movements are not essential for stereoscopic depth. *Proceedings of the Royal Society B: Biological Sciences,* 281.

McKee, S. P., & Taylor, D. G. (2010). The precision of binocular and monocular depth judgments in natural settings. *Journal of Vision, 10*, 5.

Morgan, M. J. (1979). Perception of continuity in stroboscopic motion: A temporal frequency analysis. *Vision Research, 19*, 491–500.

Morgan, M. J., & Benton, S. (1989). Motion-deblurring in human vision. *Nature, 340*, 385–386.

Morgan, M. J., & Castet, E. (1995). Stereoscopic depth perception at high velocities. *Nature, 378*, 380–383.

Ogle, K. N., & Weil, M. P. (1958). Stereoscopic vision and the duration of the stimulus. *Archives of Ophthalmology, 59*, 4–17.

R Core Team. (2017). R: A Language and Environment for Statistical Computing. Vienna.

Ramamurthy, M., Bedell, H. E., & Patel, S. S. (2005). Stereothresholds for moving line stimuli for a range of velocities. *Vision Research, 45*, 789–799.

Rawlings, S. C., & Shipley, T. (1969). Stereoscopic acuity and horizontal angular distance from fixation. *Journal of the Optical Society of America, 59*(8), 991–993.

Shipley, T., & Popp, M. (1972). Stereoscopic acuity and retinal eccentricity. *Ophthalmic Research, 3*(4), 251–255.

Shortess, G. K., & Krauskopf, J. (1961). Role of involuntary eye movements in stereoscopic acuity. *Journal of the Optical Society of America, 51*, 555.

Uttal, W. R., Davis, N. S., & Welke, C. (1994). Stereoscopic perception with brief exposures. *Perception & Psychophysics, 56*, 599–604.

Valsecchi, M., Caziot, B., Backus, B. T., & Gegenfurtner, K. R. (2013). The role of binocular disparity in rapid scene and pattern recognition. *I-Perception, 4*(2), 122–136.

Watson, A. B. (2013). High frame rates and human vision: A view through the window of visibility. *SMPTE Motion Imaging Journal, 122*, 18–32.

Watson, A. B., & Ahumada, A. J., Jr. (1985). Model of human visualmotion sensing. *Journal of the Optical Society of America, 2*, 322–342.

Westheimer, G. (1954). Eye movement responses to a horizontally moving visual stimulus. *AMA Archives of Ophthalmology, 52*(6), 932–941.

Westheimer, G., & McKee, S. P. (1975). Visual acuity in the presence of retinal-image motion. *Journal of the Optical Society of America, 65*, 847–850.

Westheimer, G., & McKee, S. P. (1977). Spatial configurations for visual hyperacuity. *Vision Research, 17*, 941–947.

Westheimer, G., & McKee, S. P. (1978). Stereoscopic acuity for moving retinal images. *Journal of the Optical Society of America, 68*, 450–455.

Wichmann, F. A., & Hill, N. J. (2001). The psychometric function: I. Fitting, sampling, and goodness of fit. *Perception & Psychophysics, 63*, 1293–1313.